DARK ENERGY SURVEY

Analysis of Filter Transmission Uniformity Specifications

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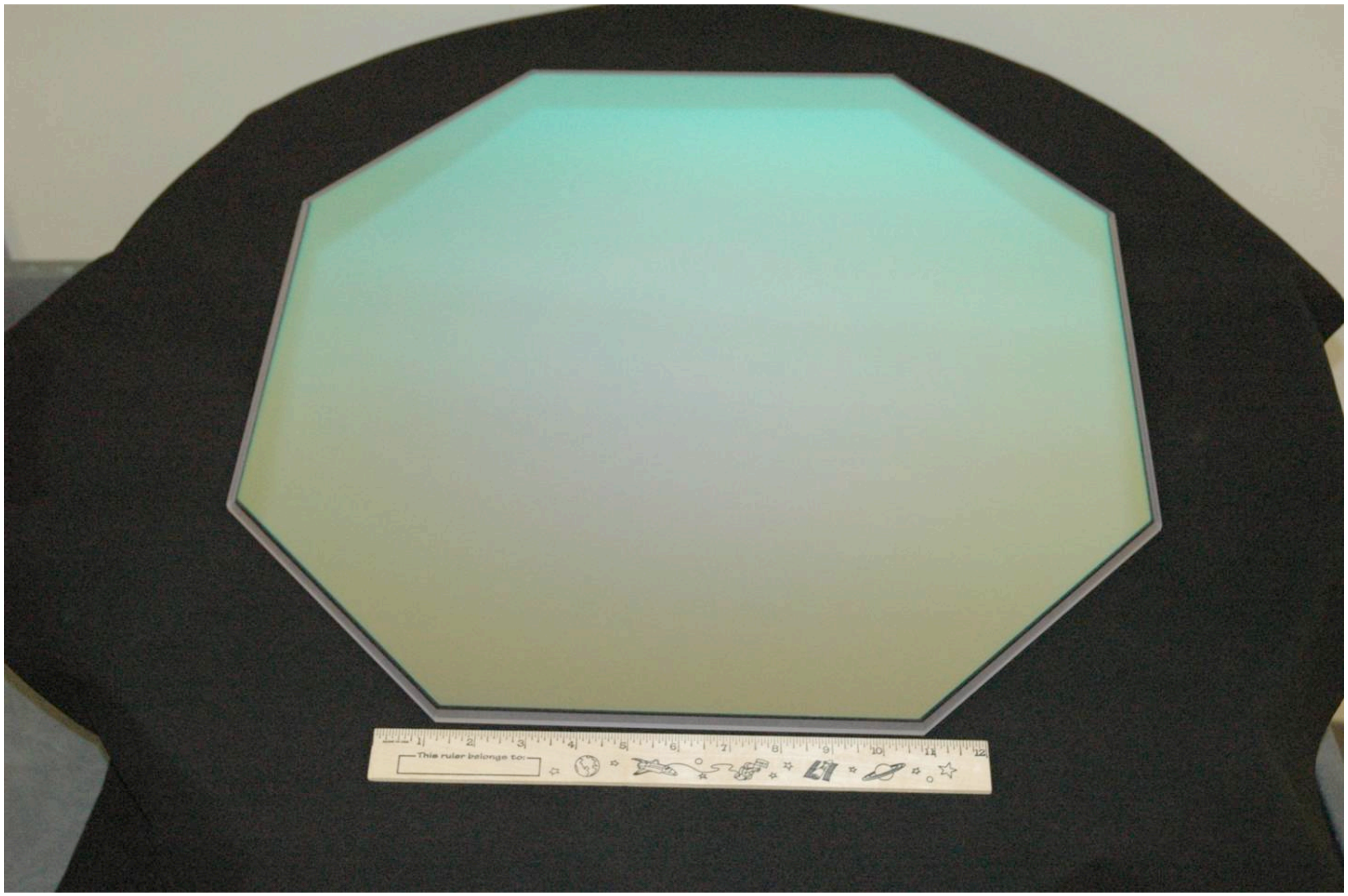
DARK ENERGY SURVEY

PanSTARRS Filters from Barr



- ***Similar to DES filters:***
  - ***570 mm size***
  - ***10 mm thick***
  - ***Fused silica substrates***
- ***Data on griz filters available***

PanSTARRS i-band filter

from B. Bigelow

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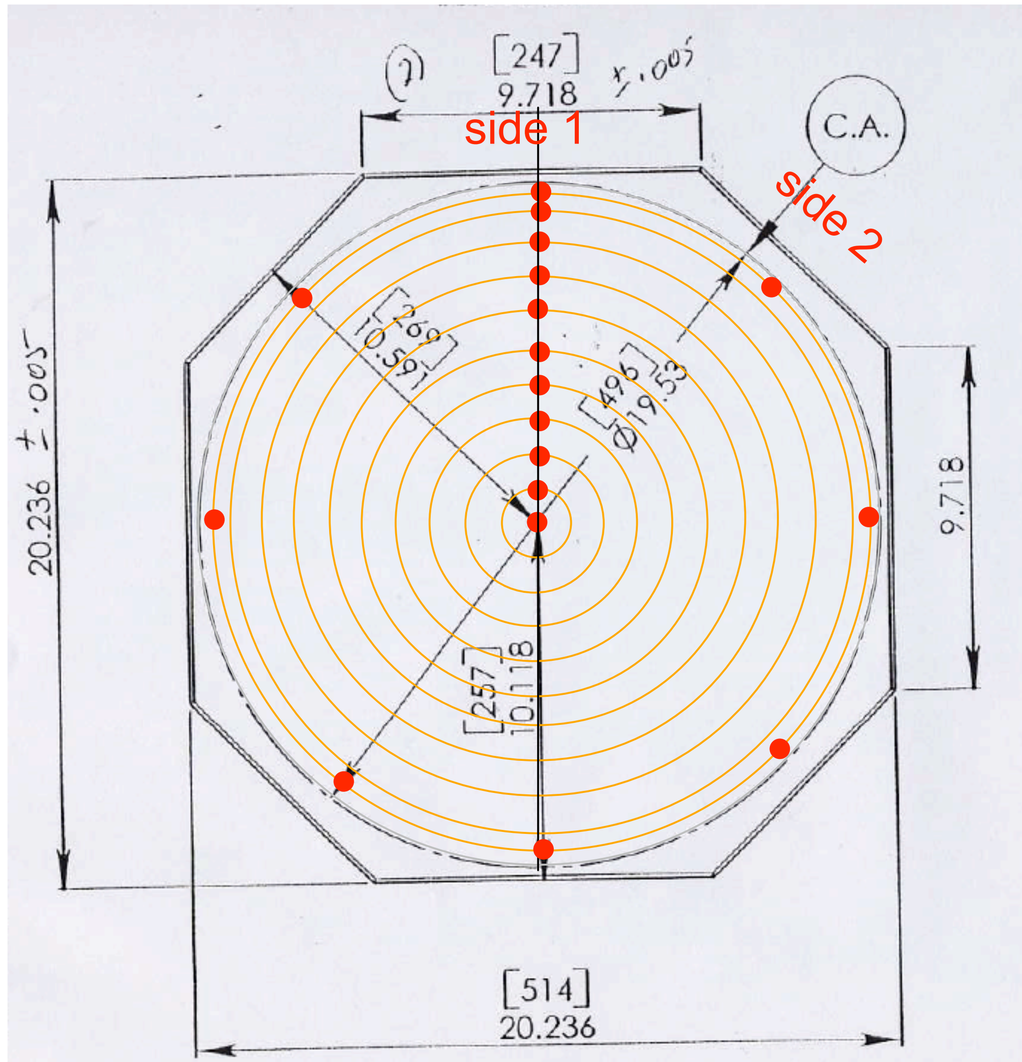
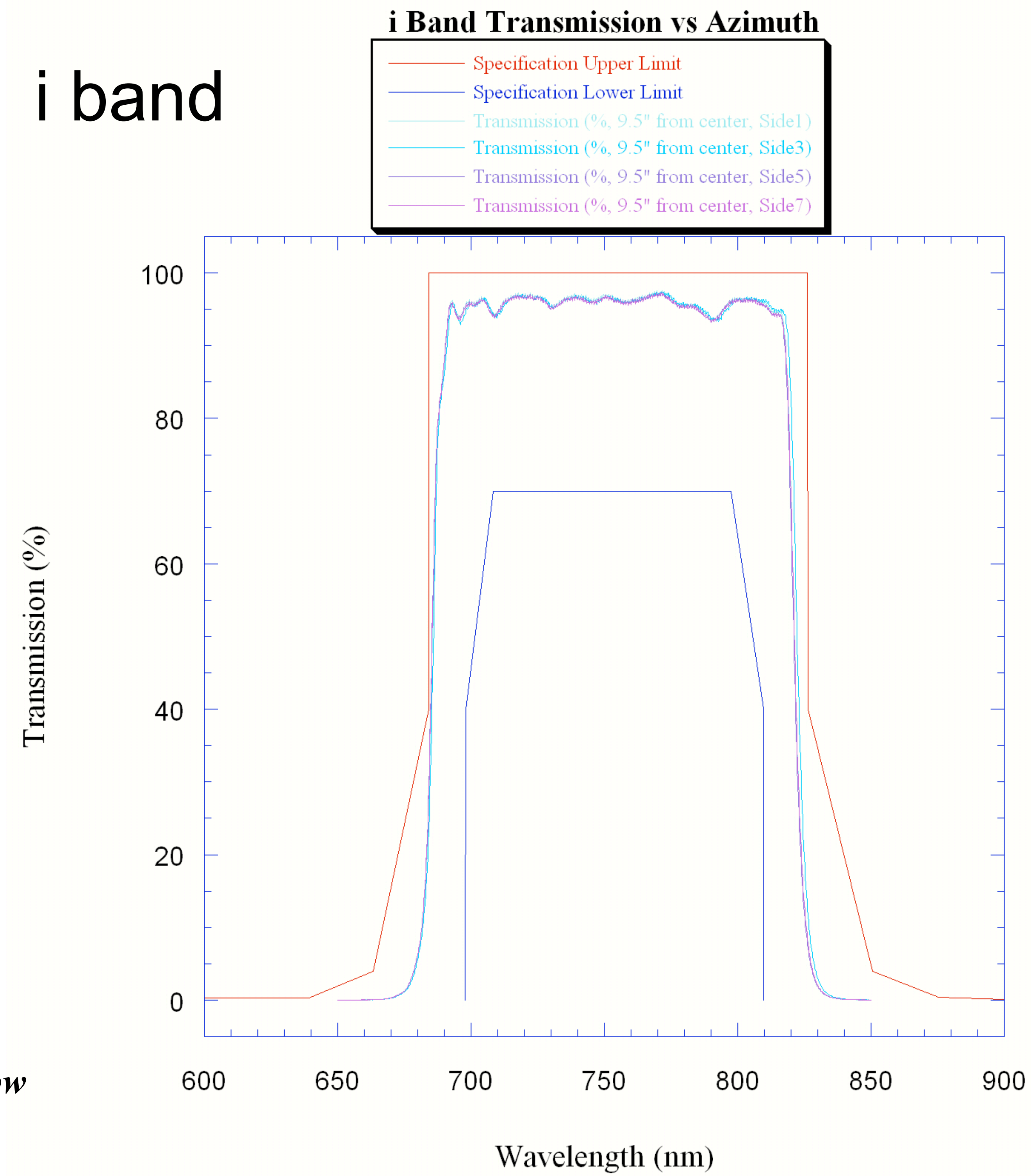
PanSTARRS Filter

- The red dots are the positions where the filters were evaluated.
- 9 *radial* points every 1”, last point at 9.5”
- I’m calling these positions 1-11, from center to edge
- Position 7 is used as reference
- Eight *azimuthal* points



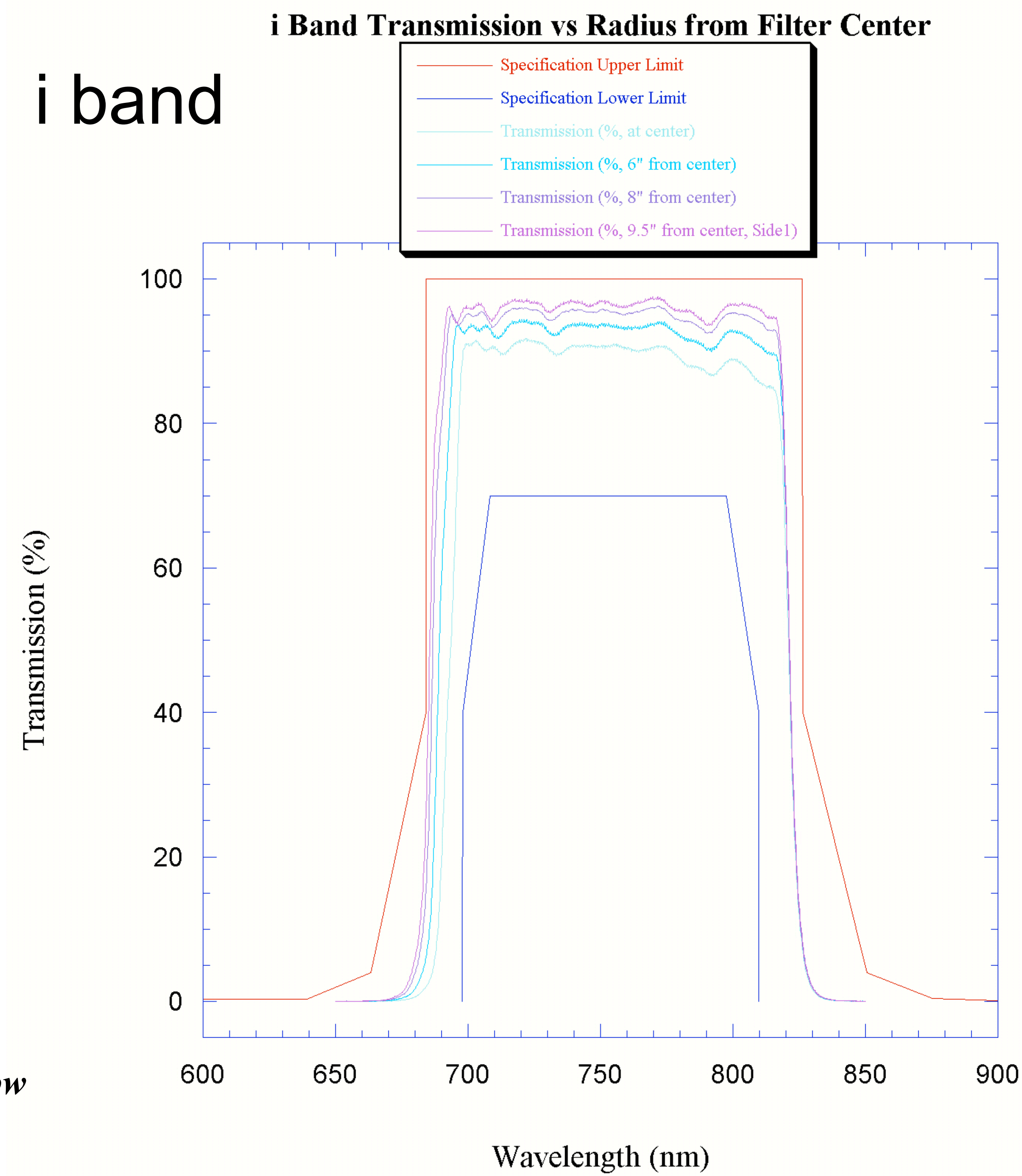
adapted from M. Schubnell

i band



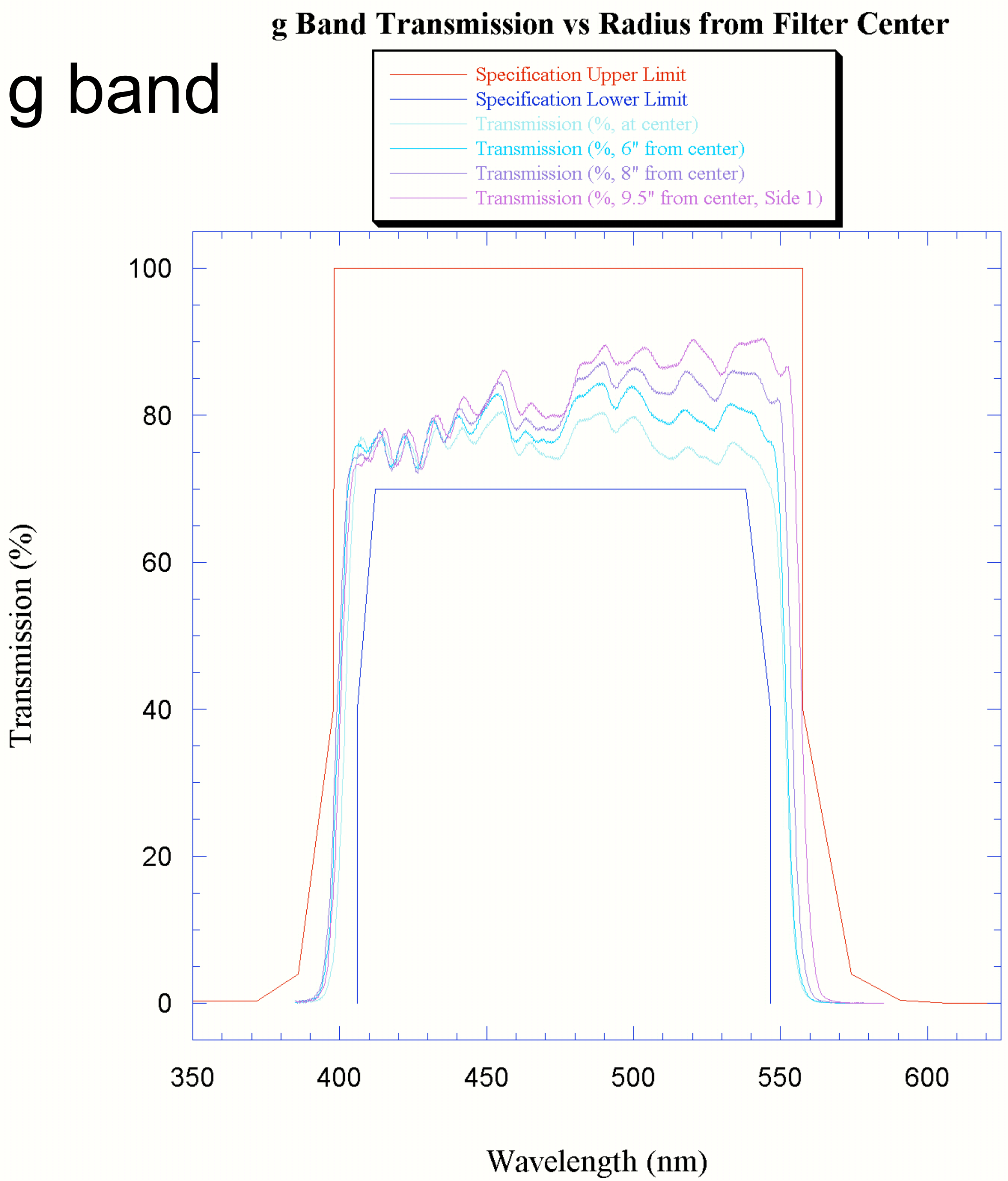
from B. Bigelow

i band



from B. Bigelow

g band



from B. Bigelow

Filter Transmission Uniformity Analysis

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- **Give filter specifications to vendors using upper and lower absolute transmission envelopes, similar to PanSTARRS filters**
- **DES photometric calibration requirement is 2%; assign 1% error budget component to filters to account for spatial non-uniformity in filter transmissions**
- **Test sets of filter curves fitting within absolute envelopes in order to specify transmission spatial uniformity requirements**
- **Use galaxy SEDs (E, Sbc, Scd, Im) from Bruzual & Charlot GISSEL package: CWW SEDs extended using theoretical models to the UV and IR**
- **Calculate fractional flux differences, vs. *average* of all test filter curves, for 4 galaxy SEDs over redshift ranges relevant to main optical spectral features: 4000Å break, [OII] 3727 and [OIII] 5007 lines**
- **Also account for transmission variations due to changes in incidence angle over focal plane**
- **Use galaxy analysis results to define "fraction envelopes" on transmission uniformity**

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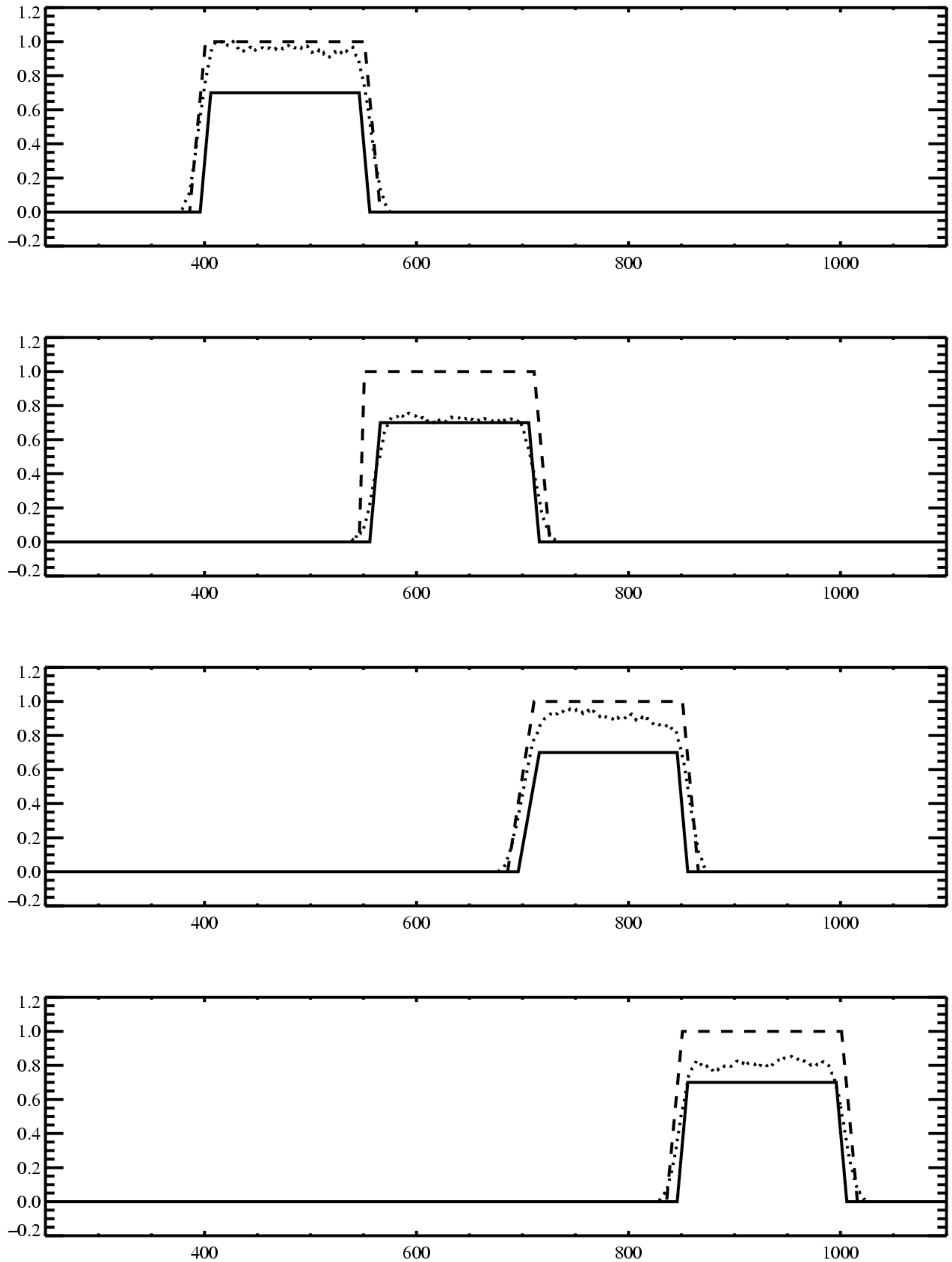

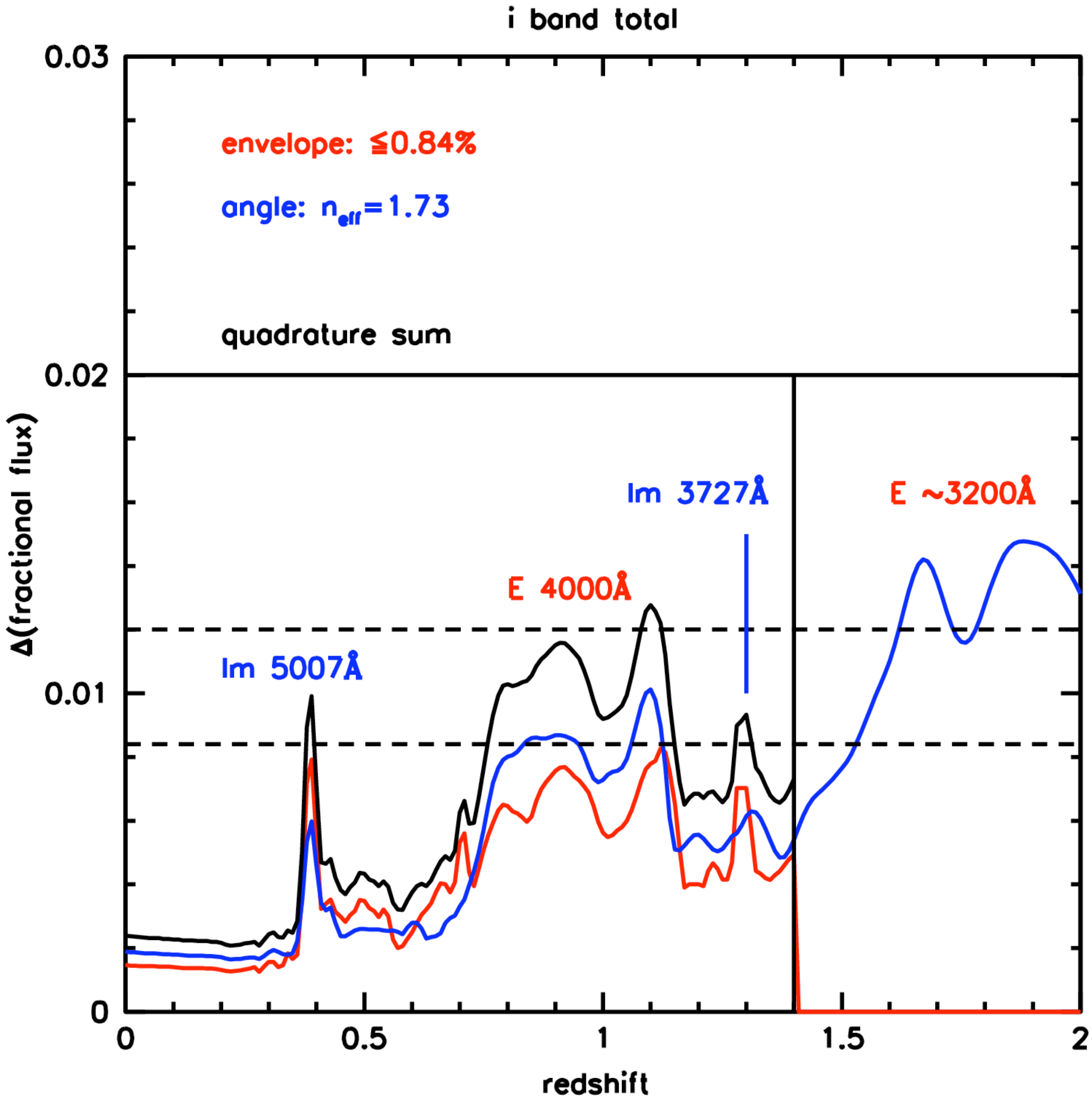

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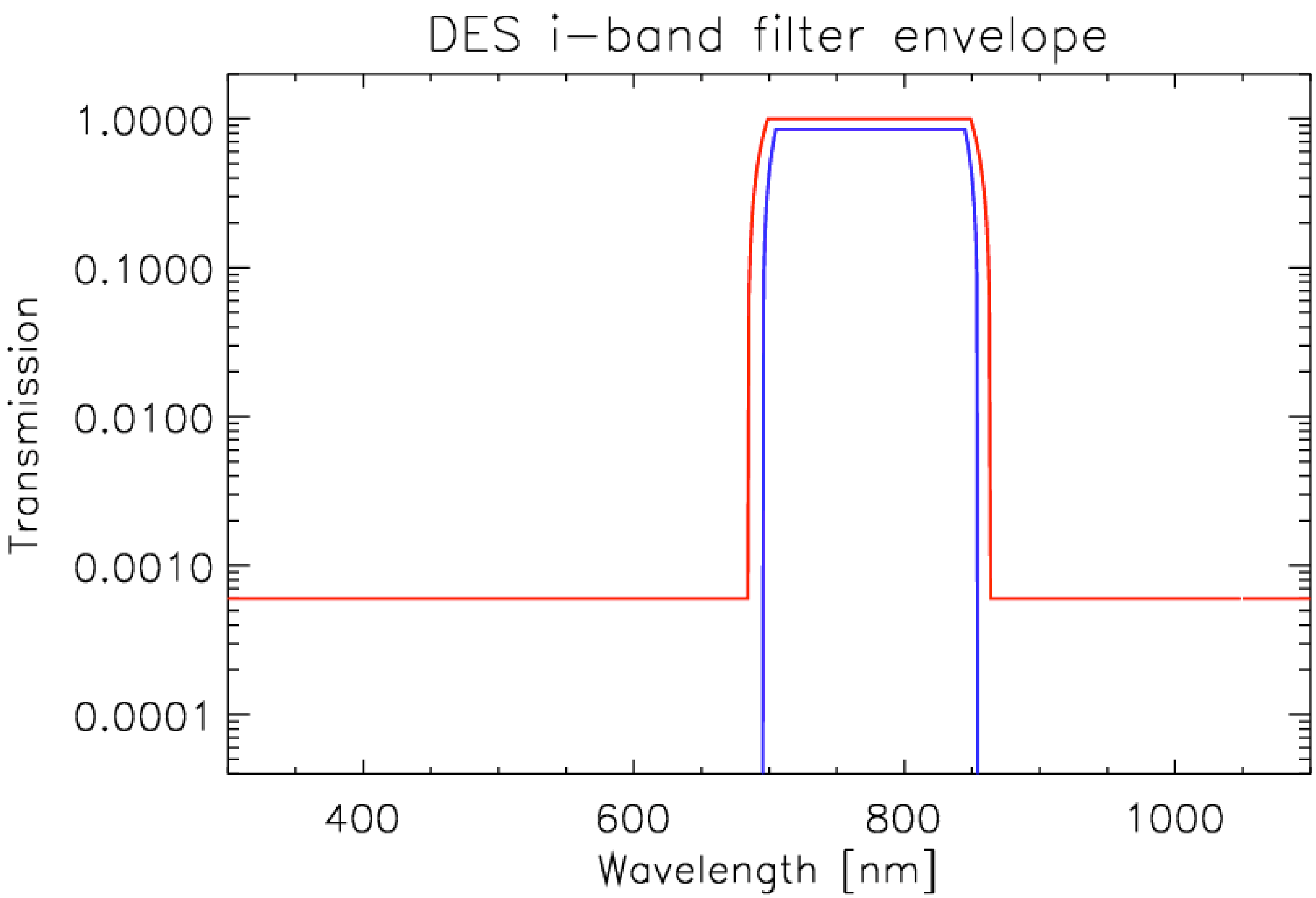
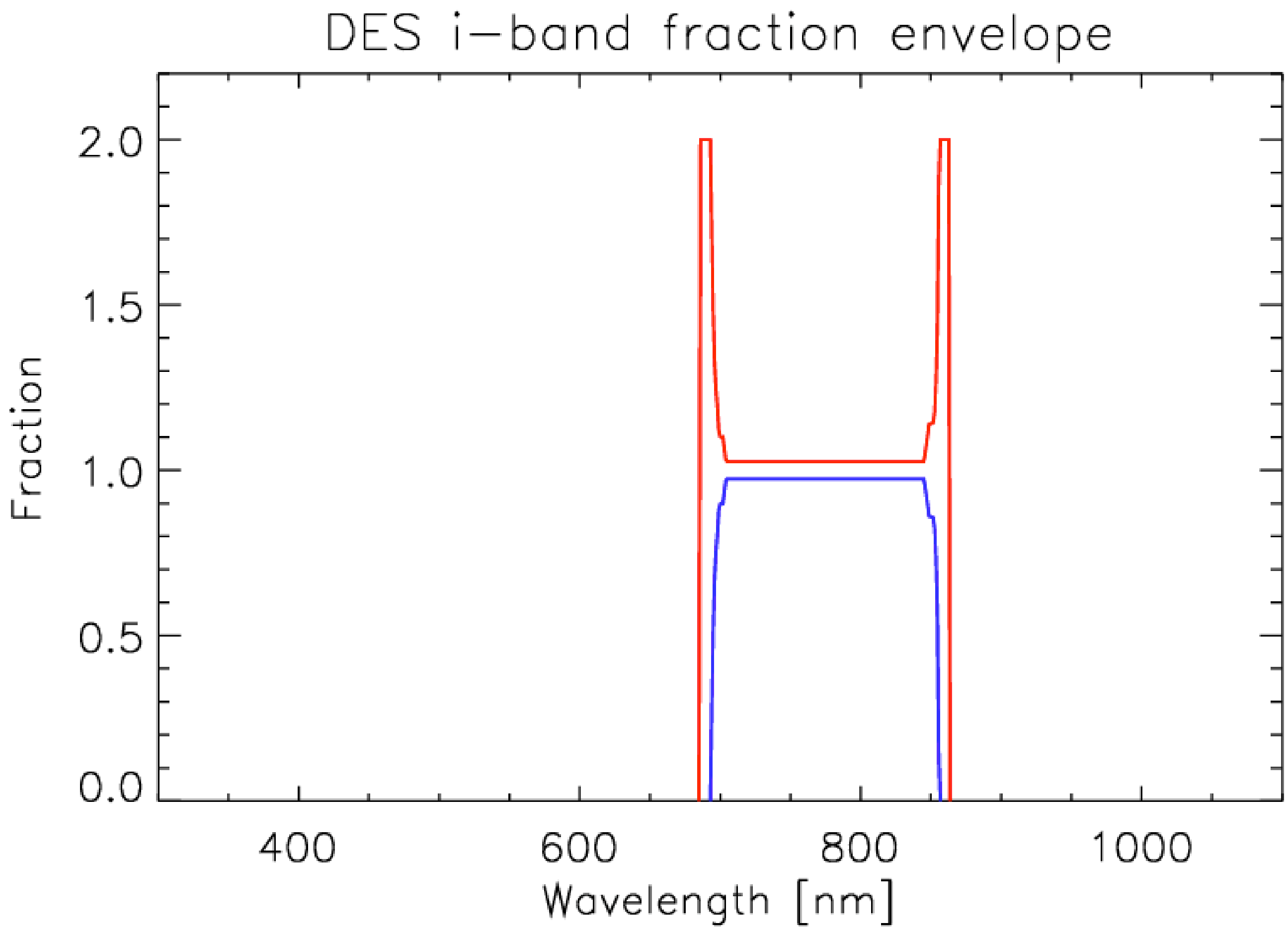
Example Absolute Transmission Envelopes for i-band Filter

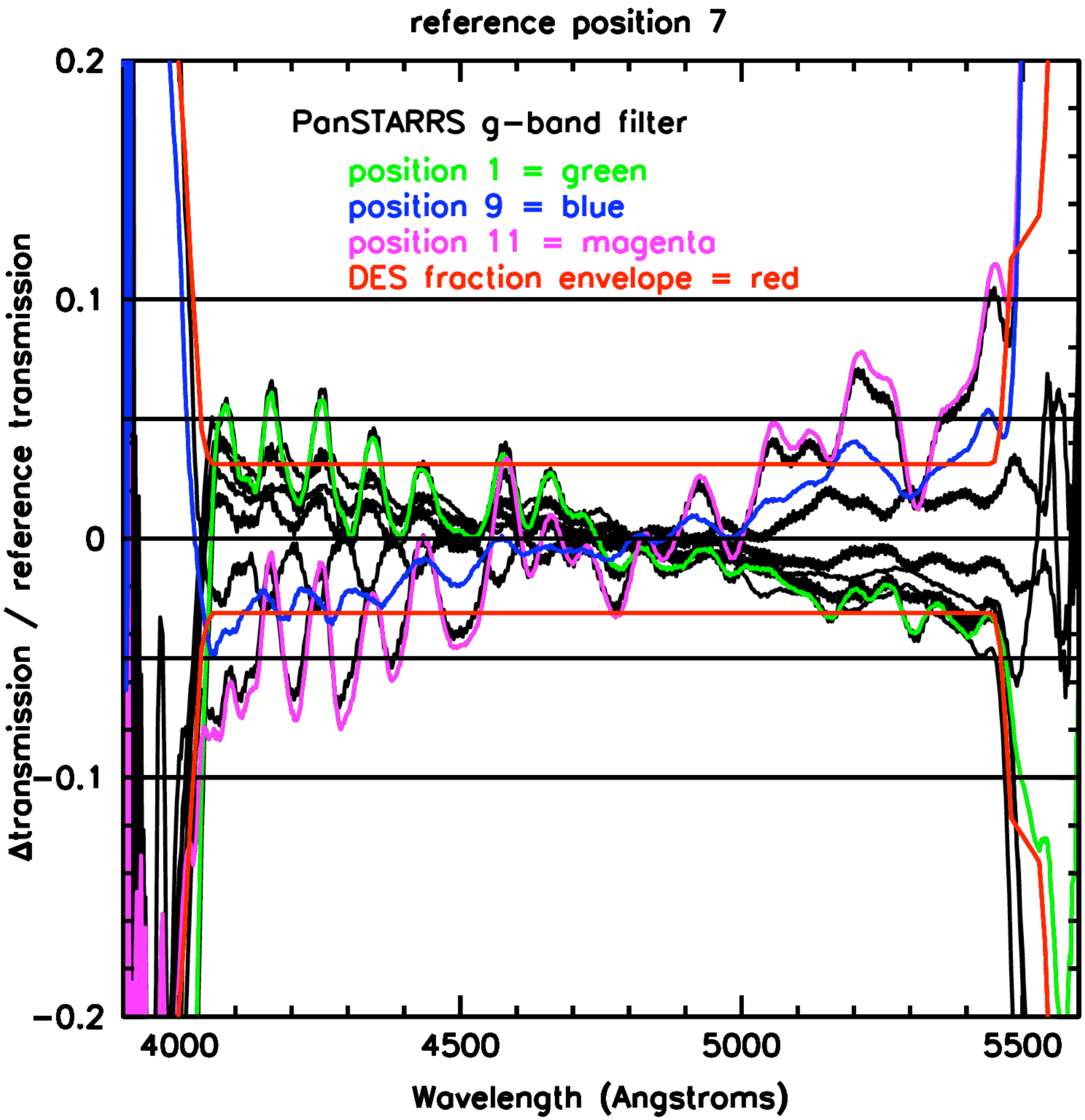


Average filter transmission required to fit within absolute transmission envelopes

Example Transmission Uniformity ("Fraction") Envelopes for i-band Filter



Shape of filter transmission relative to average required to fit within "fraction" envelopes



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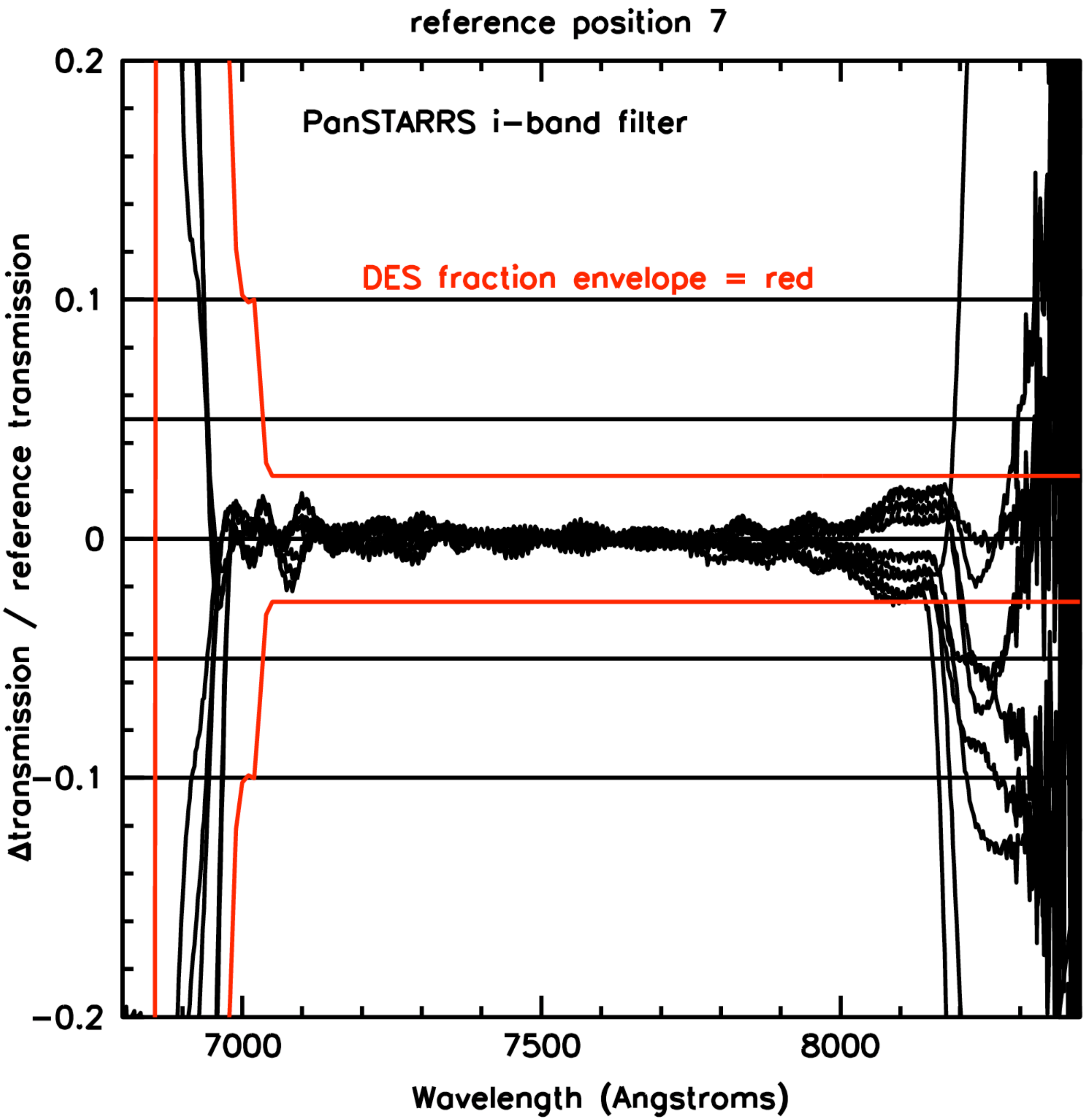

reference position 7
PanSTARRS i-band filter
DES fraction envelope = red
0.2
0.1
0
−0.1
−0.2
7000
7500
8000
Wavelength (Angstroms)
Δtransmission / reference transmission

Status

- **Derived filter transmission and spatial uniformity envelopes, based on relative photometric calibration requirements applied to galaxy spectra**

- **Contributions of "envelope" and "incidence angle" effects are about the same, for adopted 0.84% fractional flux cut used to define acceptable envelopes, and for Barr/PanSTARRS n_{eff} values**
- **Current acceptable envelopes should lead to < 1.2% fractional flux difference for galaxies**

- **Vendor responses to filter RFI (see M. Schubnell's talk) indicate it is too expensive and/or difficult to meet our current uniformity specifications, basically about 3% transmission variation over flat parts of filters**

- **Will try using color terms (which are no longer avoidable) and see if non-uniformity of Barr's PanSTARRS filters can still be acceptable for DES**
- **Derive approximate relaxed uniformity specifications**

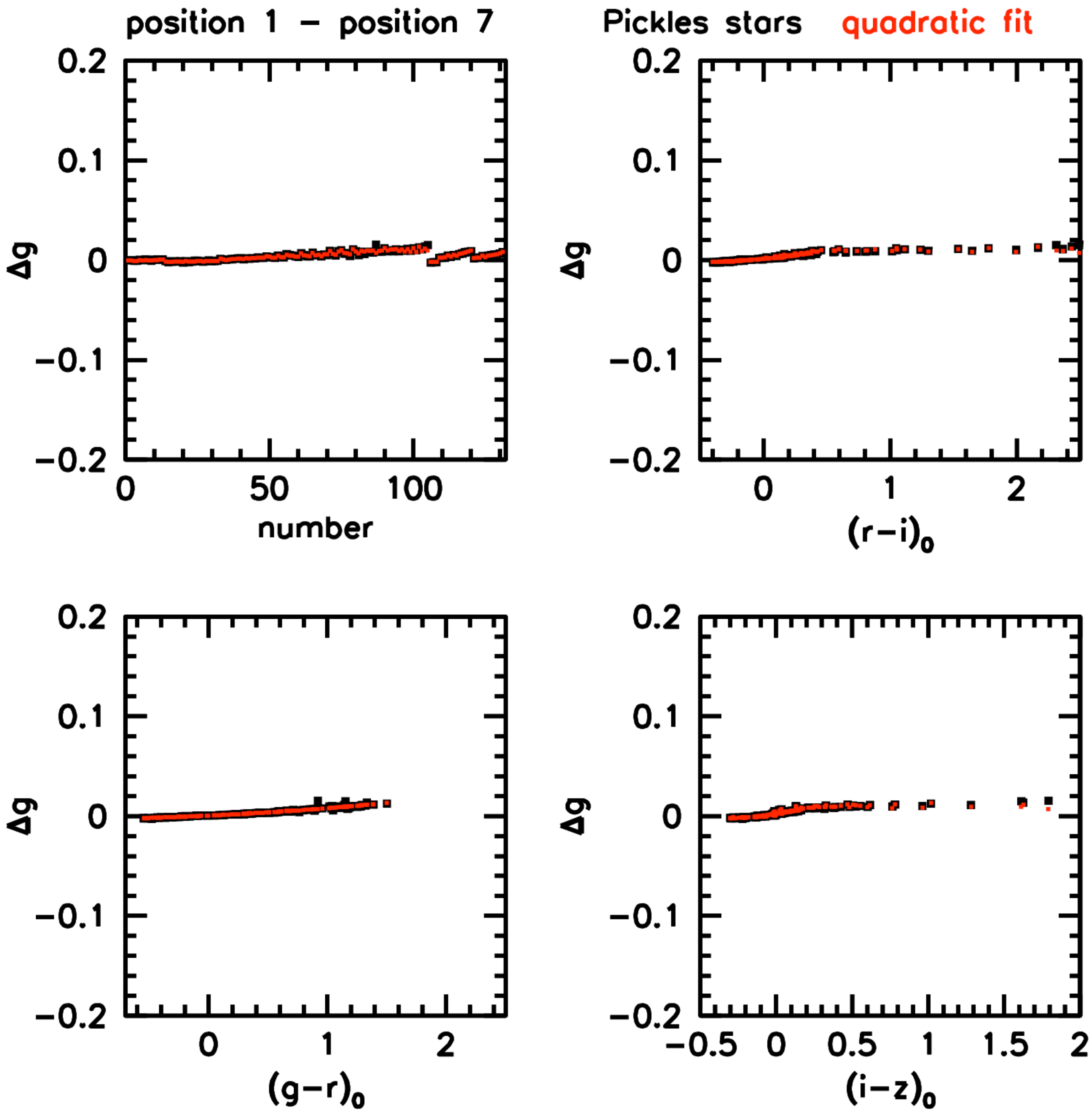
Revised Filter Transmission Uniformity Analysis, with Color Terms

- **Use measured filter transmissions at different radial positions for PanSTARRS filters**
  - **Use position 7 as reference transmission; it's approximately the median (see next slide)**
- **Also use DES filters with gradients applied to derive results more directly applicable to DES, as PanSTARRS filter bandpasses differ in detail**

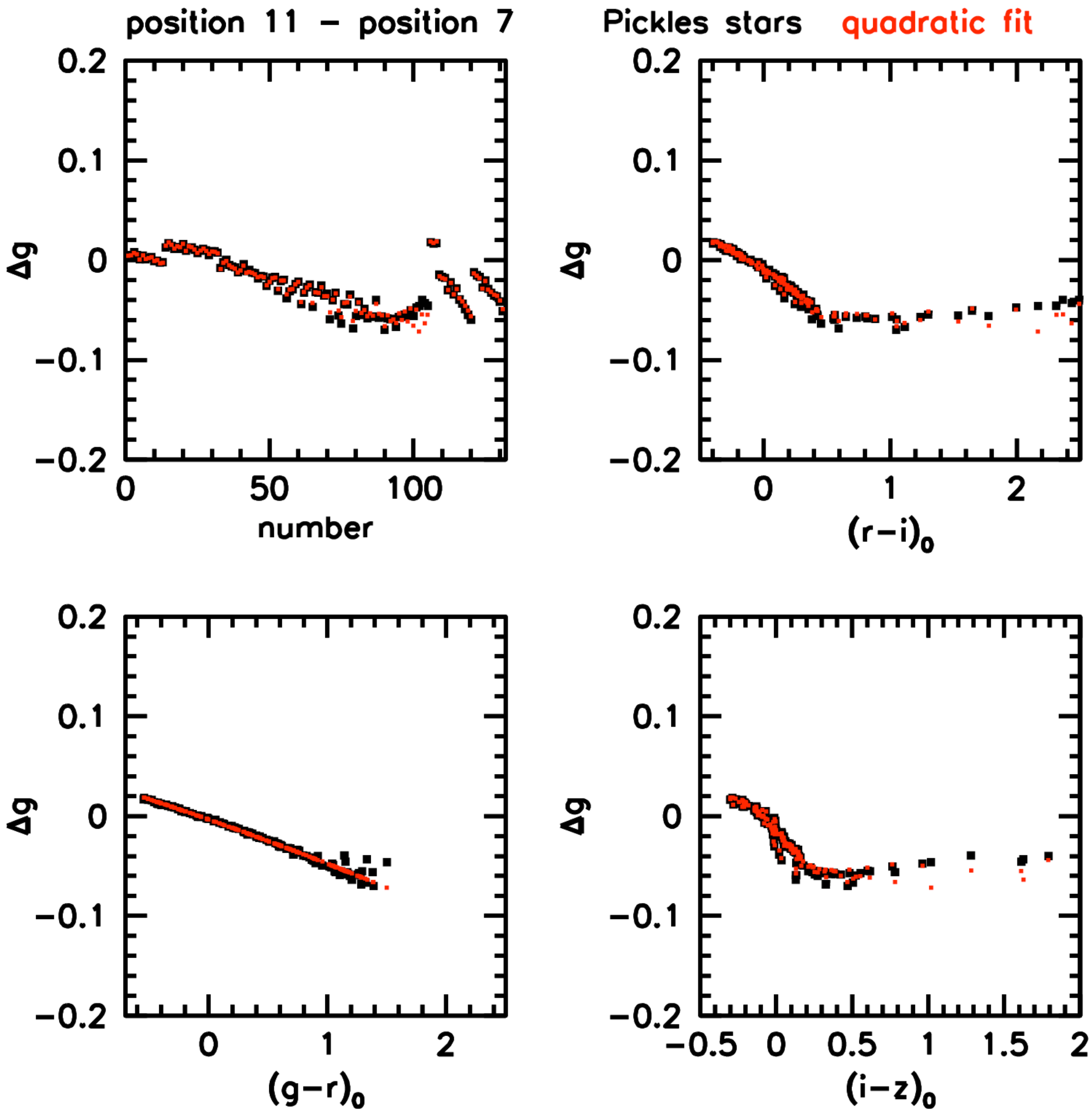
- **Use Pickles stellar library, with 131 spectra of wide range of stellar types, to derive transformations between the magnitudes at different filter positions**
- **Use quadratic fits: e.g., $g - g0 = a + b(g0-r0) + c(g0-r0)^2$**
  - **Use reference colors g-r for g, r-i for r, and i-z for i and z**

- **Use same galaxy SEDs (E, Sbc, Scd, Im) as before**
- **Also consider SN Ia "Hsiao" templates (via John Marriner) at -7, 0, +7, +14 days vs. maximum**

- **Apply color transformations from stars to galaxies and SNe and look at residuals vs. redshift and color**
- **Aim for 1% photometric errors as acceptable for the filter contribution to the total 2% error budget**


position 1 − position 7
Pickles stars
quadratic fit
Δg
0.2
0.1
0
−0.1
−0.2
0
50
100
number
1
2
(r−i)$_0$
(g−r)$_0$
−0.5
0.5
1.5
(i−z)$_0$

Stars


position 11 – position 7
Pickles stars
quadratic fit
Δg
number
(r–i)$_0$
(g–r)$_0$
(i–z)$_0$
0.2
0.1
0
–0.1
–0.2
0
50
100
1
2
–0.5
0.5
1.5

Stars

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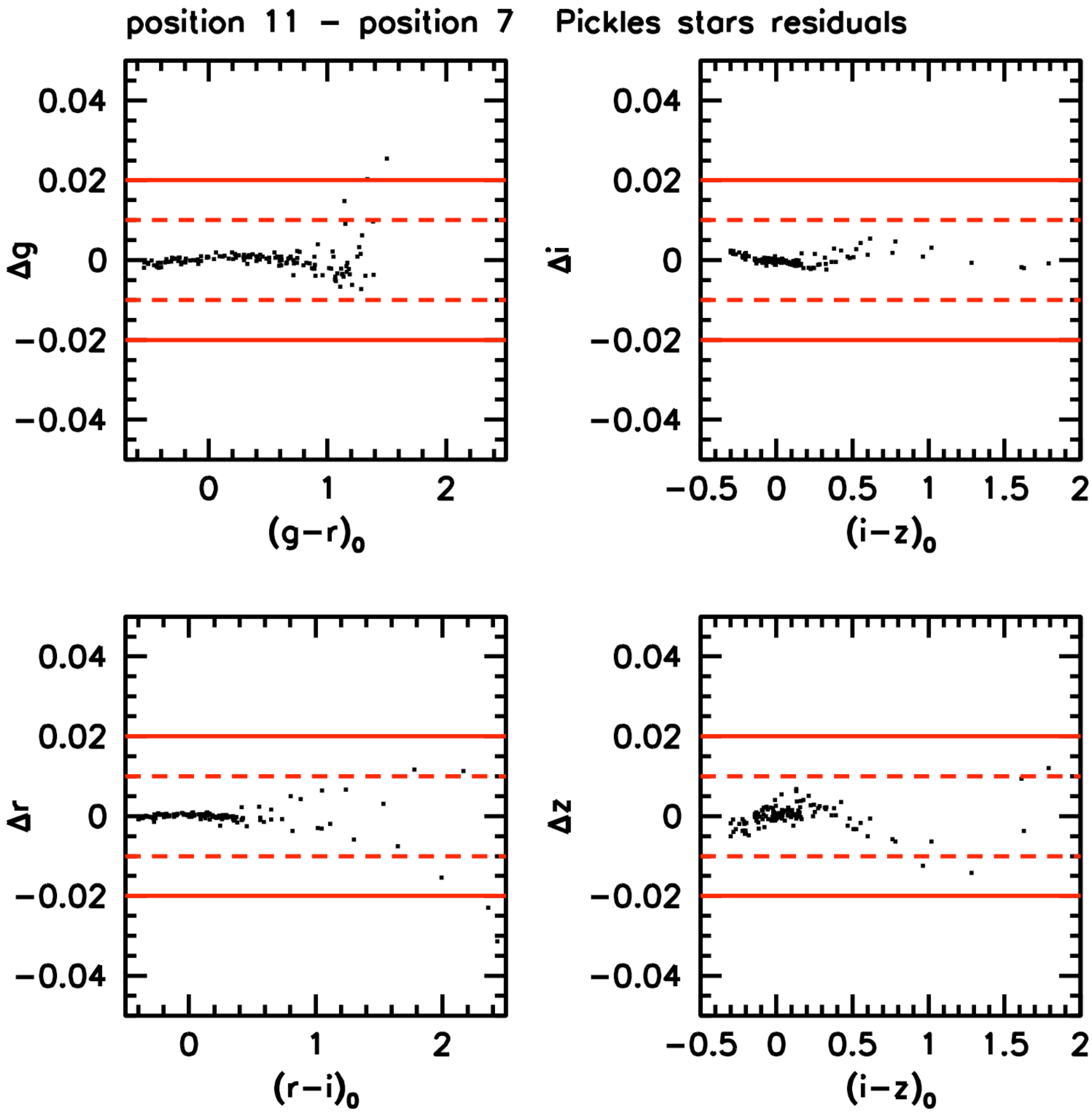
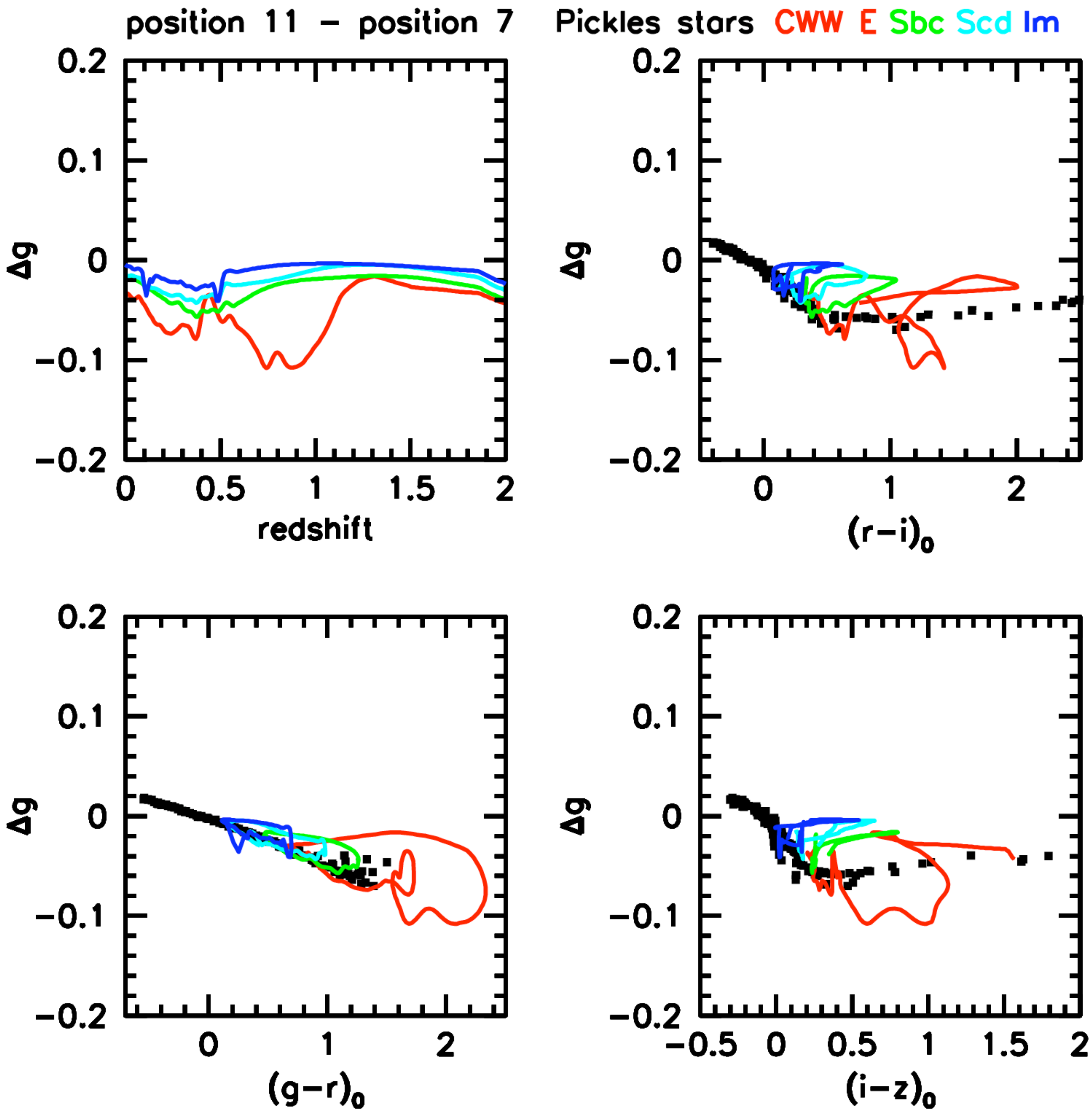


Stars


position 11 – position 7
Pickles stars CWW E Sbc Scd Im
Δg
redshift
(r−i)$_0$
(g−r)$_0$
(i−z)$_0$

Galaxies

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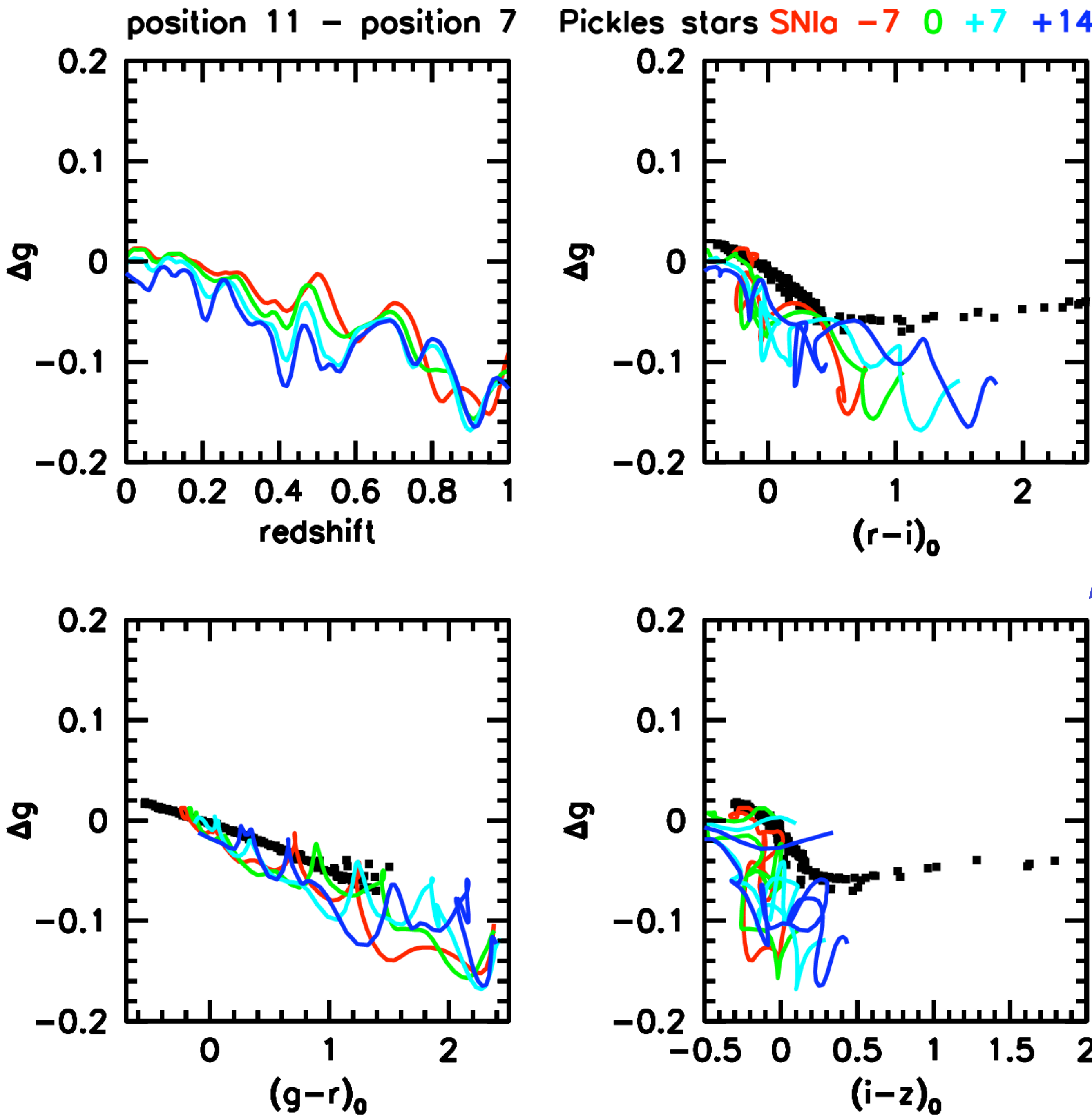
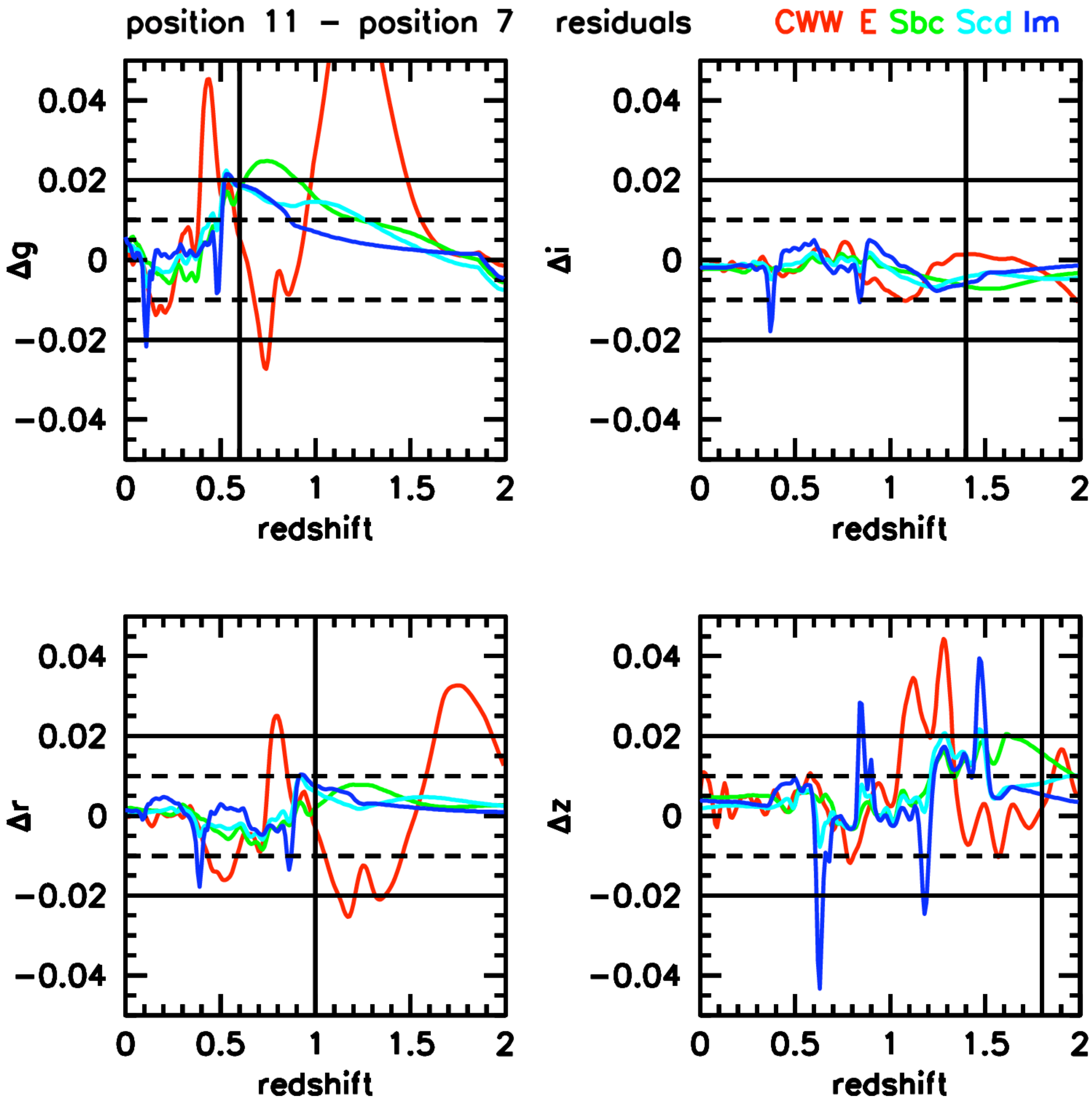
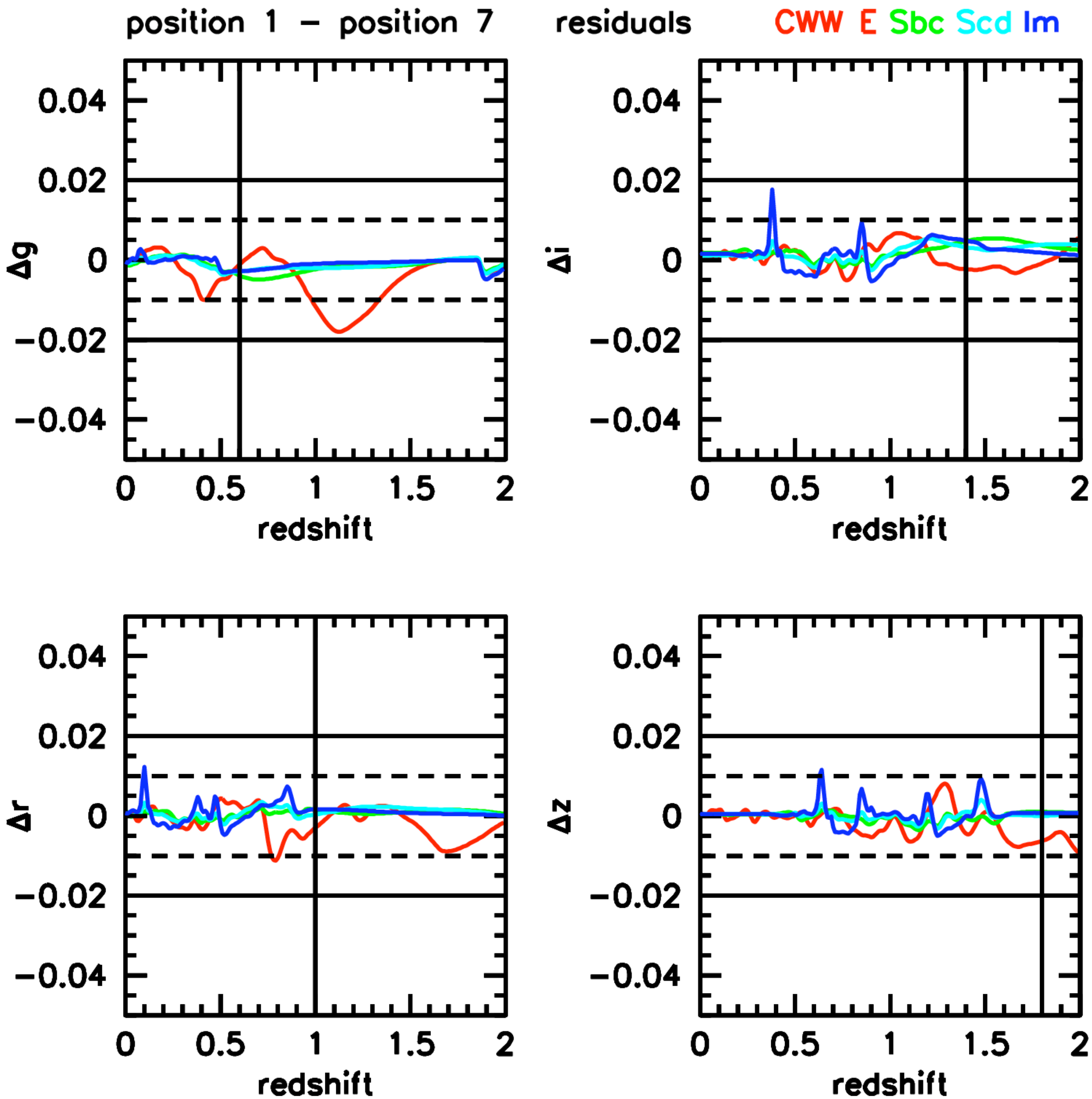


Type Ia Supernovae



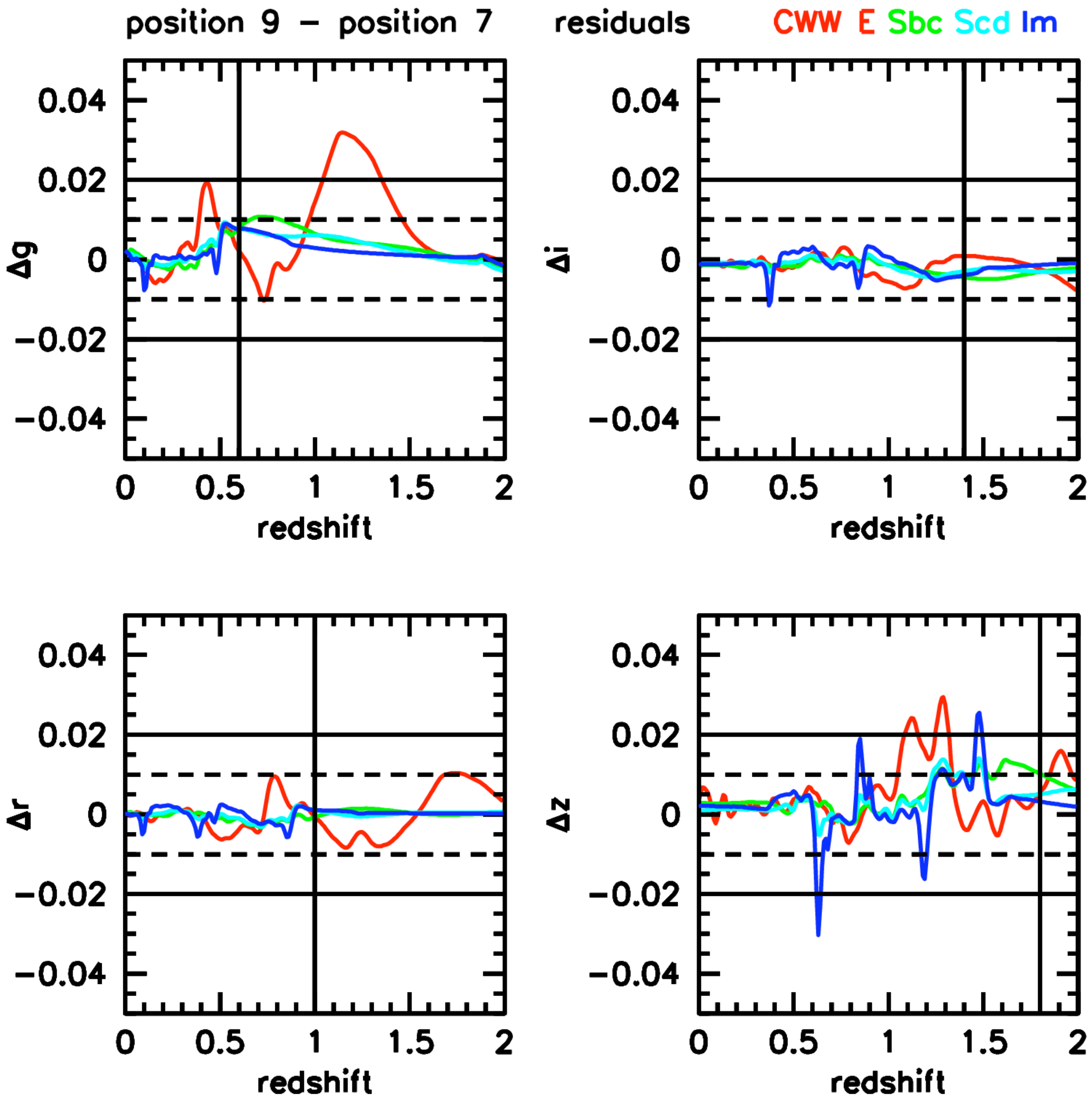
position 11 – position 7 residuals
CWW E Sbc Scd Im
Δg
Δi
Δr
Δz
0.04
0.02
0
−0.02
−0.04
0 0.5 1 1.5 2
redshift

Bad



position 1 – position 7
residuals
CWW E Sbc Scd Im
Δg
Δi
Δr
Δz
0.04
0.02
0
−0.02
−0.04
0
0.5
1
1.5
2
redshift

Good



position 9 – position 7 residuals
CWW E Sbc Scd Im
Δg
Δi
Δr
Δz
0.04
0.02
0
−0.02
−0.04
0
0.5
1
1.5
2
redshift

Ok

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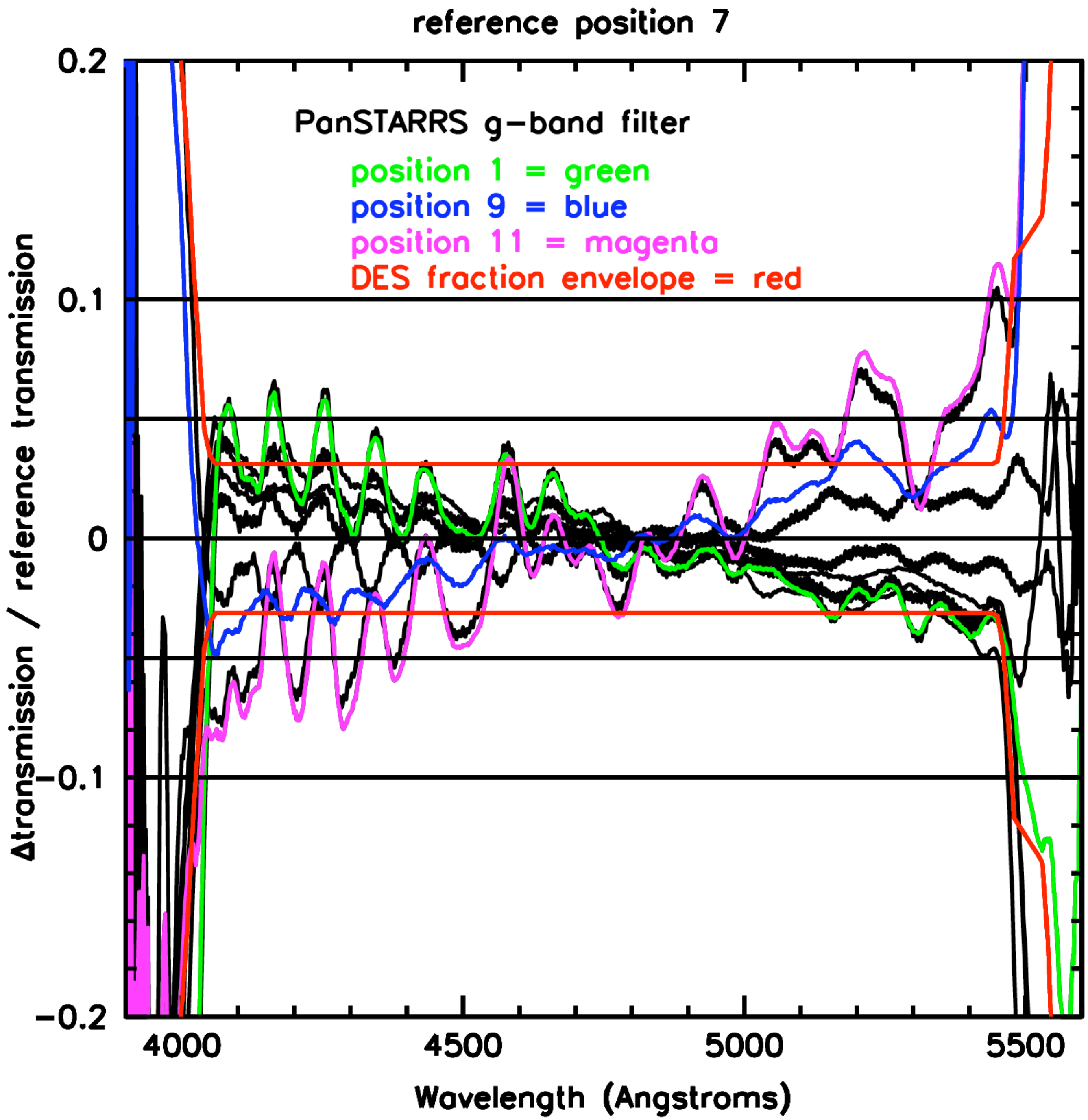

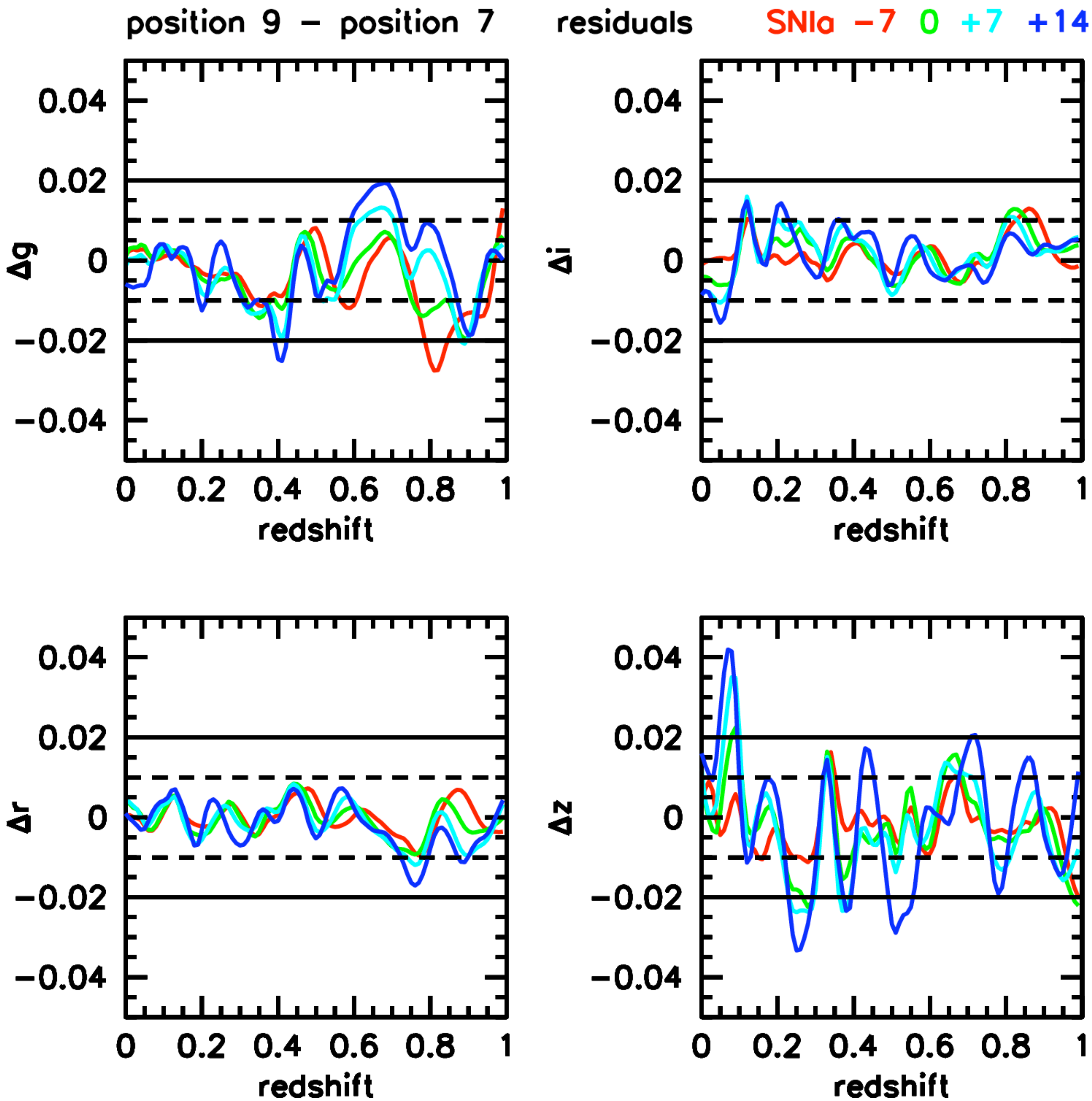
position 9 – position 7 residuals SNIa –7 0 +7 +14
Δg
Δi
Δr
Δz
0.04
0.02
0
–0.02
–0.04
0 0.2 0.4 0.6 0.8 1
redshift

Ok ?

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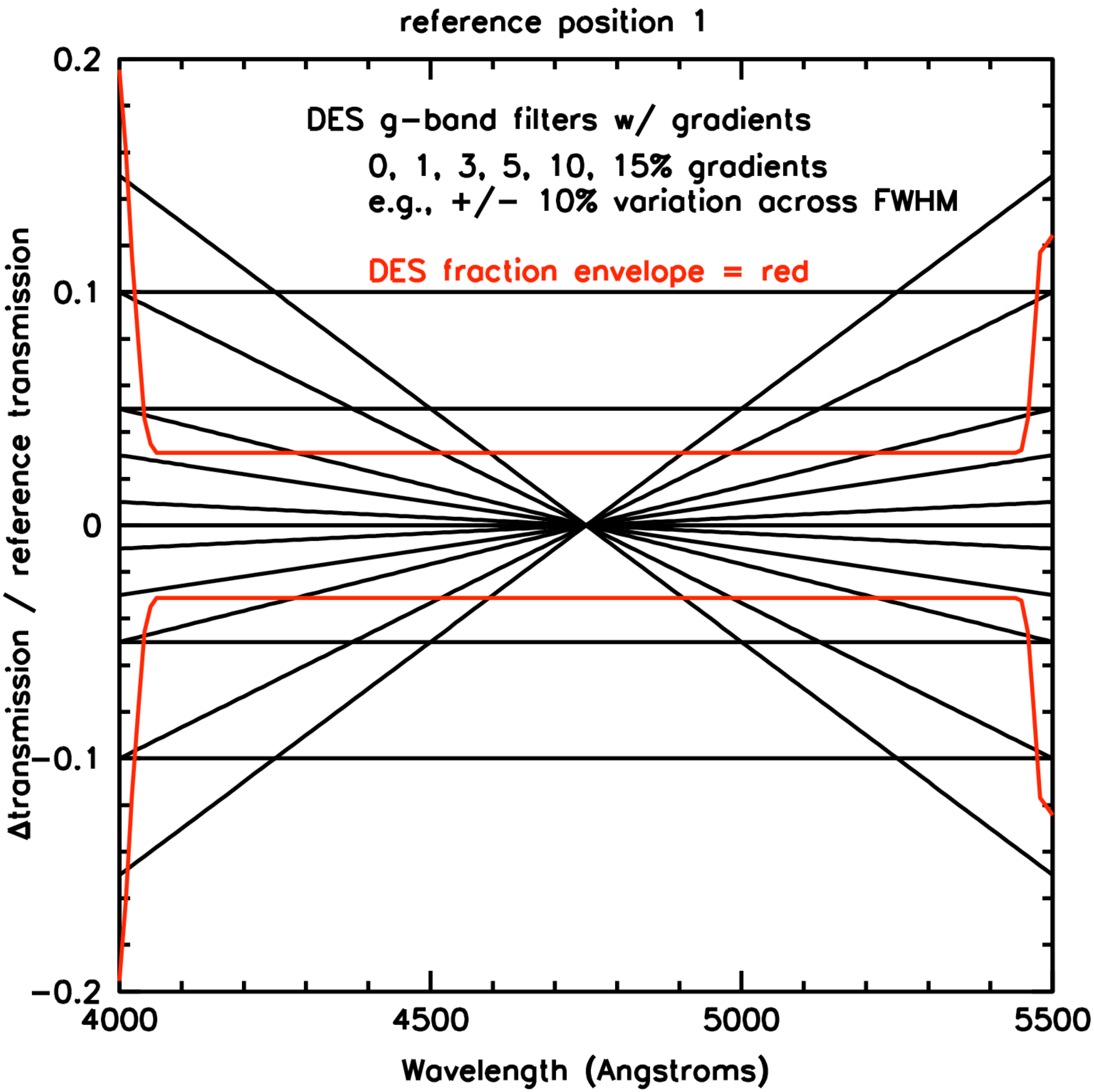
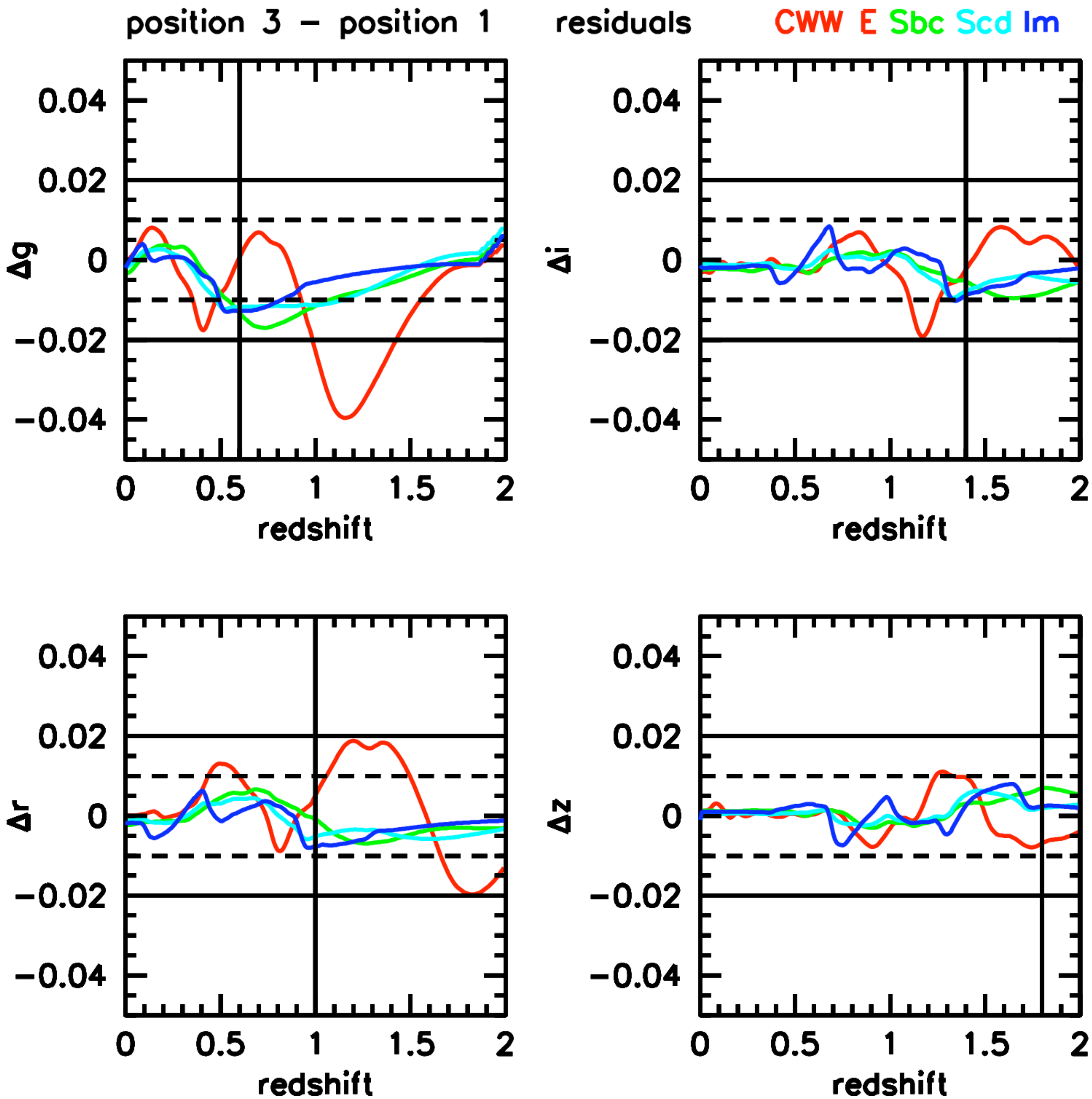
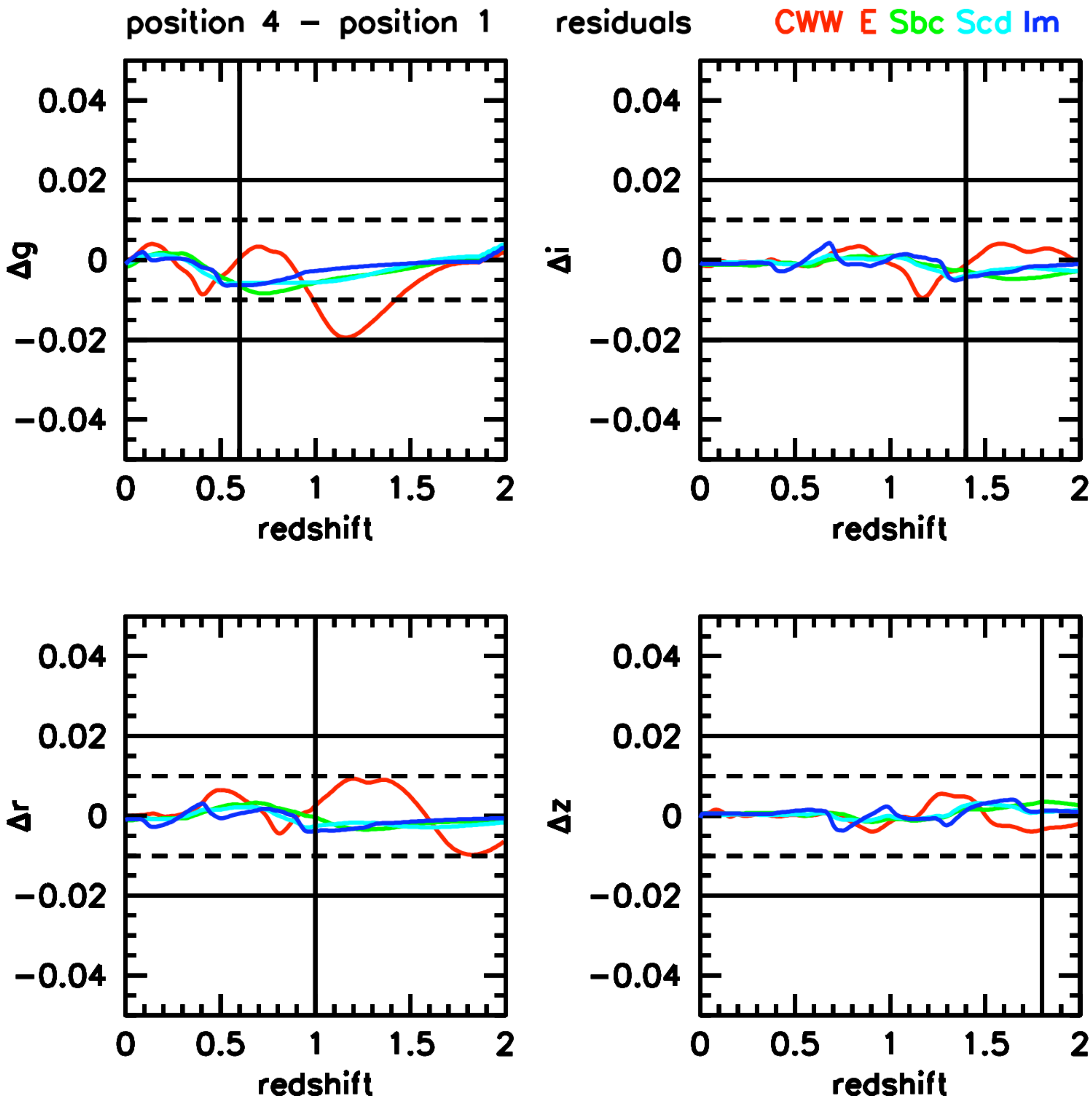
SURVEY





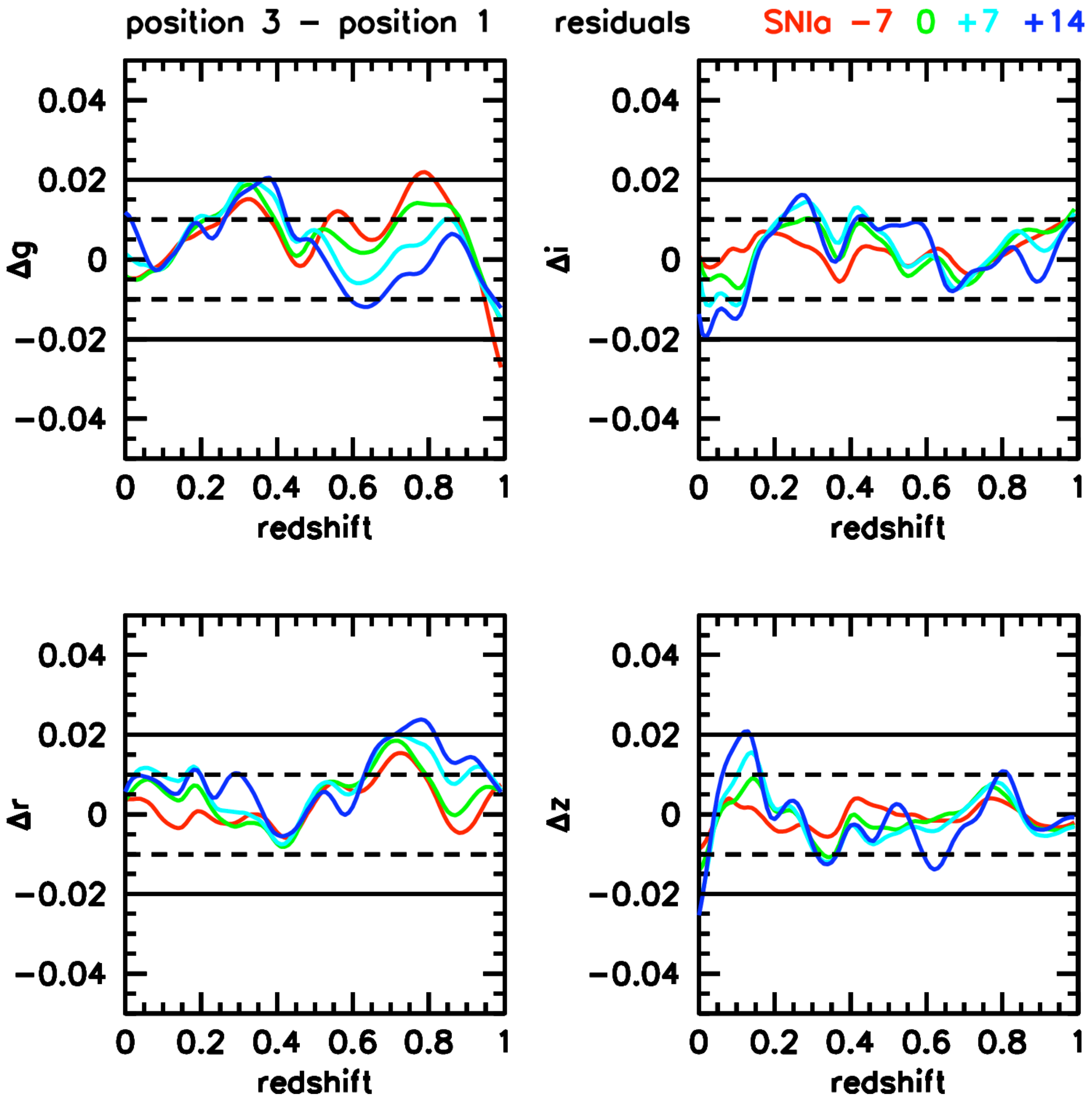
Galaxies

10% gradient filters



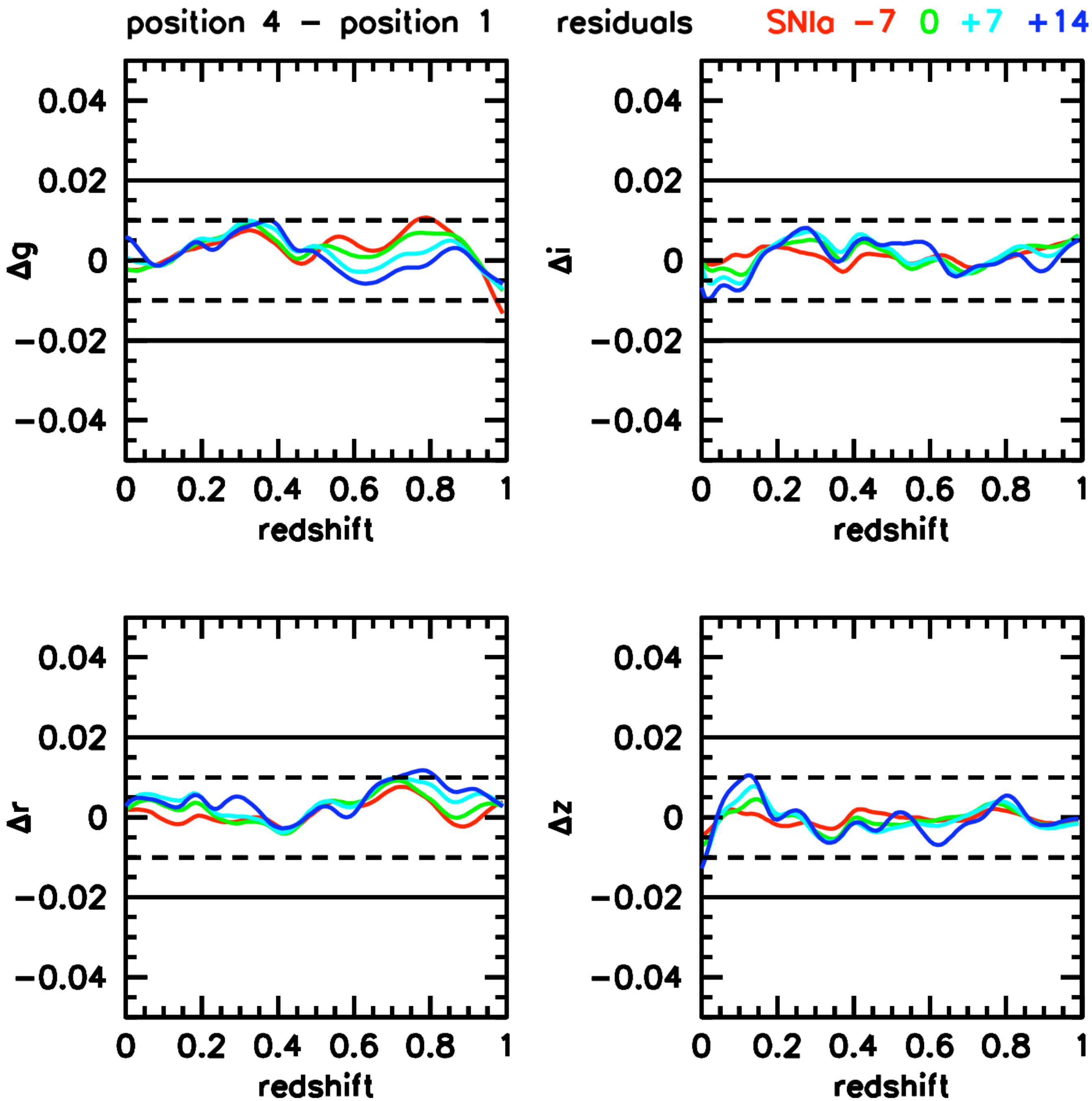
Galaxies

5% gradient filters



SNe Ia

10% gradient filters



SNe Ia

5% gradient filters

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Conclusions and Coadds

- **Relaxed transmission uniformity specifications possible, by using color terms based on stars, and applying to galaxies and SNe Ia**
  - **Approximately 5-10% uniformity required to keep filter photometric error contribution to <~ 1%**
  - **About 2-3 times less stringent than original ~3% uniformity specification when color terms not allowed**
  - **PanSTARRS filters from Barr can nearly meet this**

- **Should extend analysis to use "trial filter curves", as before**

- **Calibration including position-dependent color terms straightforward for catalogs of single-epoch images, but how to apply optimally to catalogs for coadded images (just use average)?**
  - **Also probably not possible to account for color terms in actual image coaddition step**
  - **Can benefit from sqrt(Ntiles) reduction in errors if object positions uncorrelated in different tilings; probably not true for g and r where there are only 4 tilings**

Extra Slides

DECam Filter Wavelengths and Transmission Requirements

from DECam Technical Specifications (document #806)

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- **TO.15 Filter transmission requirements: > 85% in [*g*, *r*, *i*, *z*]**
- **Table 3 Filter Transmission Requirements**

filter	CWL (nm)	FWHM(nm)	Transmission
g	475	150	85%
r	635	150	85%
i	775	150	85%
z	925	150	85%

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Top Level Photometric Calibration Science Requirements (version 6.5 draft of document)

- **S-16 The magnitudes of an object may be calculated to within 2% by convolving the spectrum of the object with the system response curves. This requirement assumes that the spectra are spectrophotometrically calibrated and that the system response curves are absolute.**
  - ***This is the total photometric calibration requirement***

- **S-17 The magnitudes vary only by –2.5 log f_2/f_1, independent of position in the final map to within 2% (1% enhanced goal), where f_2/f_1 is the ratio of photon fluxes. This is to be true in *g, r, i, z* individually.**
  - ***This is basically the relative photometric calibration requirement***
  - ***We'll focus on this***

- **S-18 The magnitudes have an absolute zero point that is well-defined and known to 0.5%. The magnitudes will be on the natural instrument system.**
  - ***This is basically the absolute photometric calibration requirement***

Proposed Relative Photometric Calibration Science Requirements

- **S-19** **Uncorrected nonlinearities** due to imperfect shutter timing and nonlinear CCD/amplifier gain shall be less than 0.3%, measured as the peak error between shortest and longest exposure times, and between the faintest and brightest unsaturated stars.
- **S-20** The **aperture correction** shall have an internal rms error no bigger than 0.6% for any CCD and seeing between 0.8” and 1.5”.
- **S-21** The rms photometric errors due to **imperfect flatfielding** (including errors in removing the ghost image of the night sky and removing other stray light sources) will be no worse than 0.84%.
- **S-22** The rms photometric variations due to spatial changes in the **shape of the system optical transmission** (telescope, corrector lenses and coatings, and filters) will be no worse than 0.84%.
- **S-23** The rms photometric variations due to spatial changes in the **shape of the CCD QE vs. wavelength** curve will be no worse than 0.84%.
- **S-24** The rms photometric errors due to imperfect removal, using the global relative photometric calibration solution, of temporal and spatial changes in the **atmospheric transparency and extinction**, will be no worse than 0.84%.
- **S-25** The rms photometric errors due to imperfect corrections for **astrometric and other distortions** on the focal plane (including those due to the optical design and to the CCD “glowing edges”) will be no worse than 0.84%.

- **Kept 1st two requirements at 0.3% and 0.6%**
- **Leaves remaining 1.88% for last 5 terms, divide by sqrt(5) to get 0.84% per requirement**

Trial Vendor Filter Specification Curves

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- **Give filter specifications to vendors using upper and lower transmission envelopes, similar to PanSTARRS filters**
- **Test a set of filter curves (100 per filter), provided by Tim McKay to fit within a trial set of filter envelopes**
- **Galaxy SEDs (E, Sbc, Scd, Im) from Bruzual & Charlot GISSEL package: CWW SEDs "extended" using theoretical models to the UV and IR**
- **Calculate fractional flux differences, vs. *average* of all test filter curves, for 4 galaxy SEDs over these redshift ranges (focus on 4000Å break, [OII] 3727 and [OIII] 5007 lines):**
  - **$z < 0.6$ for g**
  - **$z < 1.0$ for r**
  - **$z < 1.4$ for i**
  - **$z < 1.8$ for z, Z, Y**
- **Adopt flat f_λ flatfield source**
- **Accept/reject filter curves using nominal 0.84% filter budget number for fractional flux difference**

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Trial Filter Envelopes

filter	wavelength	renormalization range ("flat" region)
g	4000-5500	4150-5350
r	5600-7100	5750-6950
i	7000-8500	7150-8350
z	8500-10000	8650-9850
Z	8500-9700	8650-9550
Y	9700-10200	9850-10050

- **Envelopes from Tim McKay**
  - **Upper envelope**
    - **0% at 150 A below turn-on wavelength**
    - **100% from turn-on to turn-off**
    - **0% by 150 A above turn-off**
  - **Lower envelope**
    - **0% at 50 A below turn-on wavelength**
    - **85% from turn-on +50 A to turn-off -50A**
    - **0% by 50 A above turn-off**

- **I also renormalized them, within "flat" region indicated, to focus on the shape differences**

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Shifted bandpasses at different incidence angles

Bandpasses after weighting by intercepted filter areas

Final sum of area-weighted bandpasses

Parker et al. (2005)

H

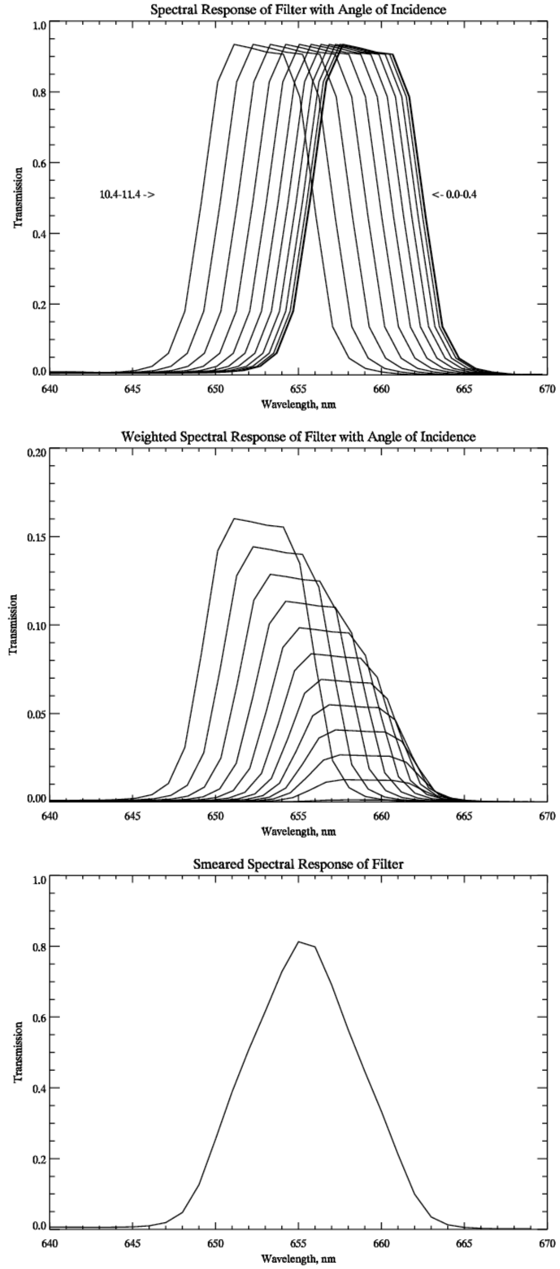

Figure 4. Blue-shifting response of interference filter in converging UKST beam as one moves out from the centre of the field. Top plot (a) shows the shift for each concentric ring of the beam; the second plot (b) shows these shifted response curves weighted according to the area of the ring. The final plot (c) shows the summed, smeared out filter transmission curve. The central wavelength of this smeared profile is 6550 Å and the FWHM is 80 Å.

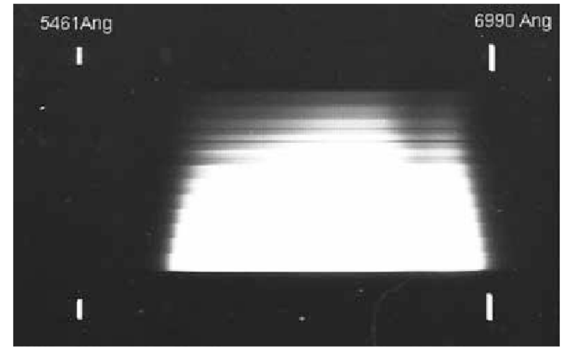

Figure 5. Calibration spectrograph result of the effective SR bandpass as a function of wavelength from the combination of the red OG590 filter and the Tech-Pan emulsion.

and survey productivity. Field rotation and atmospheric differential refraction can adversely affect longer exposures (Watson 1984), which are also more susceptible to short-term weather and seeing variations. The associated 15-min broad-band SR exposures were taken through the OG590 red filter. At this exposure level, they are well matched to the depth of continuum point-sources on the matching Hα exposure. For completeness, we include in Fig. 5 the effective SR bandpass as a function of wavelength obtained from a calibration spectrogram for the OG590 filter in combination with the Tech-Pan emulsion.

With photographic surveys, the magnitude limit for a given survey field is not a fixed parameter but is a function of factors such as seeing, hypersensitization and development of the films after exposure, emulsion batch variations and the brightness of the night-sky. Nevertheless, it is clear from comparison with the generally deeper, standard UKST *R*-band survey data that the approximate magnitude limit for a typical Hα survey field in an equivalent *R* magnitude for continuum point sources is $\sim$20.5 (Arrowsmith & Parker 2001). This value can be directly determined by examining the number magnitude counts from the matched Hα, SR and *R* band SuperCOSMOS Image Analysis Mode (IAM) data (see later) for a given field and determining the point where completeness breaks down. As an illustration, we give magnitude limit estimates for continuum point sources in A and B grade exposures of two Hα survey fields in Table 2.

Additionally, the use of the same emulsion for both Hα and SR exposures ensures an excellent correspondence of their image PSFs when film pairs are taken under the same observing conditions. The intention was to take the Hα and SR exposures consecutively as far as possible. This greatly simplifies the inter-comparability of both types of exposure. Of the 233 survey fields, only 100 are in fact sequential pairs while most of the rest were taken a few days apart. However, 45 fields had a gap of one or more years between the Hα

Table 2. The depth of each of the four original images measured in R equivalent magnitudes.

Exposure number	Survey field	Survey grade	Histogram num/mag peak (R equiv. magnitude)

Angle of Incidence Effects

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- **See analyses in Rienstra (1998, Proc. SPIE, 3377, 267) and in Parker et al. (2005, MNRAS, 362, 689)**

- **Use Snell's law to relate angle of incidence θ_{inc} from air, effective index of refraction n_{eff} of filter, and angle θ in filter by**
    - $n_{eff} \sin\theta = \sin\theta_{inc}$ **(n = 1 for air)**
    - $\theta = \sin^{-1}(\sin\theta_{inc} / n_{eff})$
- **Wavelengths (e.g., center wavelength, half-power points) will then be shifted by**
    - $\lambda = \lambda_0 \cos\theta = \cos[\sin^{-1}(\sin\theta_{inc} / n_{eff})]$

- **For a range of incidence angles, also need to weight transmissions by area of circular annulus intercepted by the filter for each incidence angle**

- **Effects**
    - **Wavelengths shift to the blue**
    - **Bandpass shape also changes**

Angle of Incidence Effects

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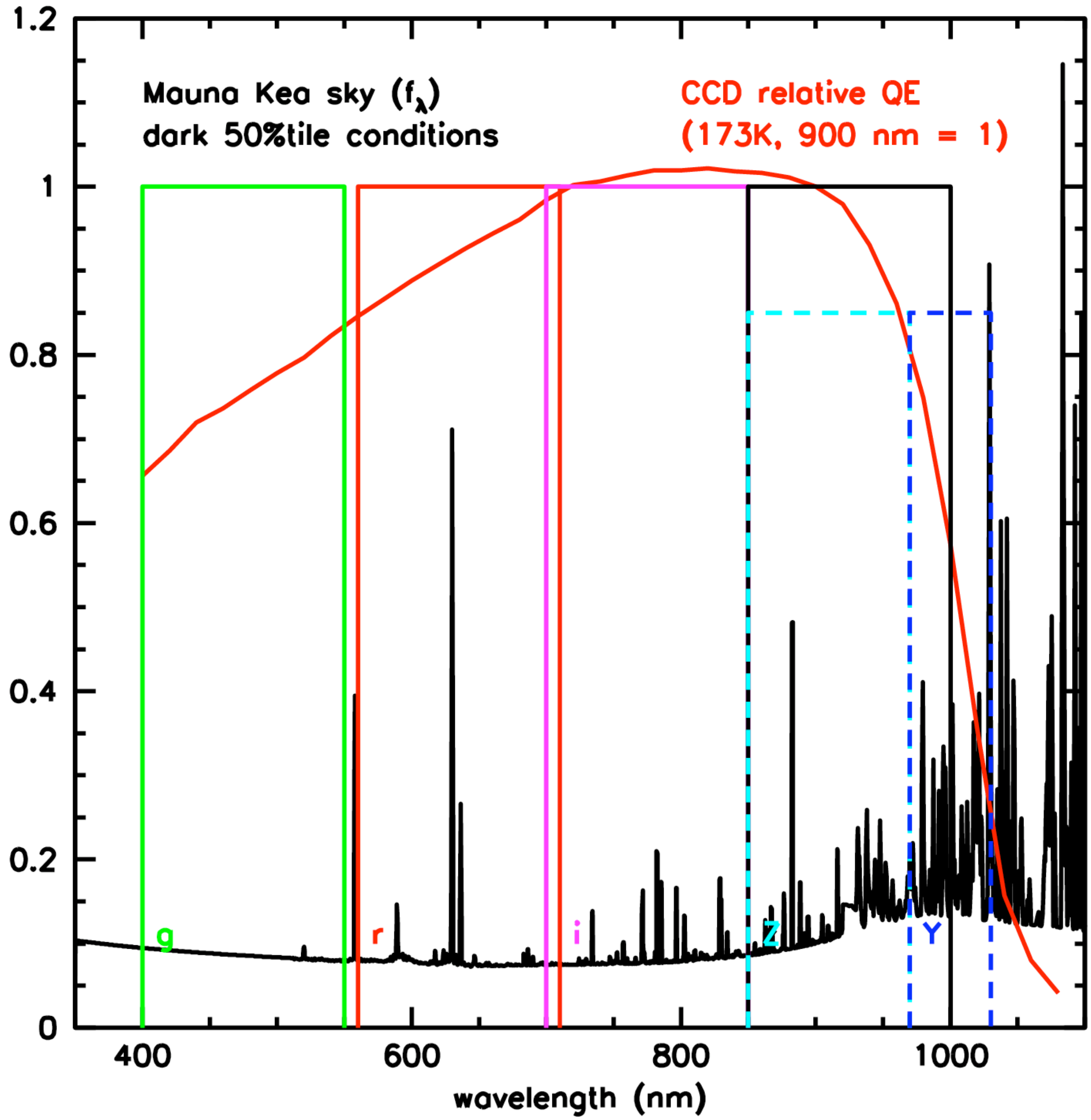
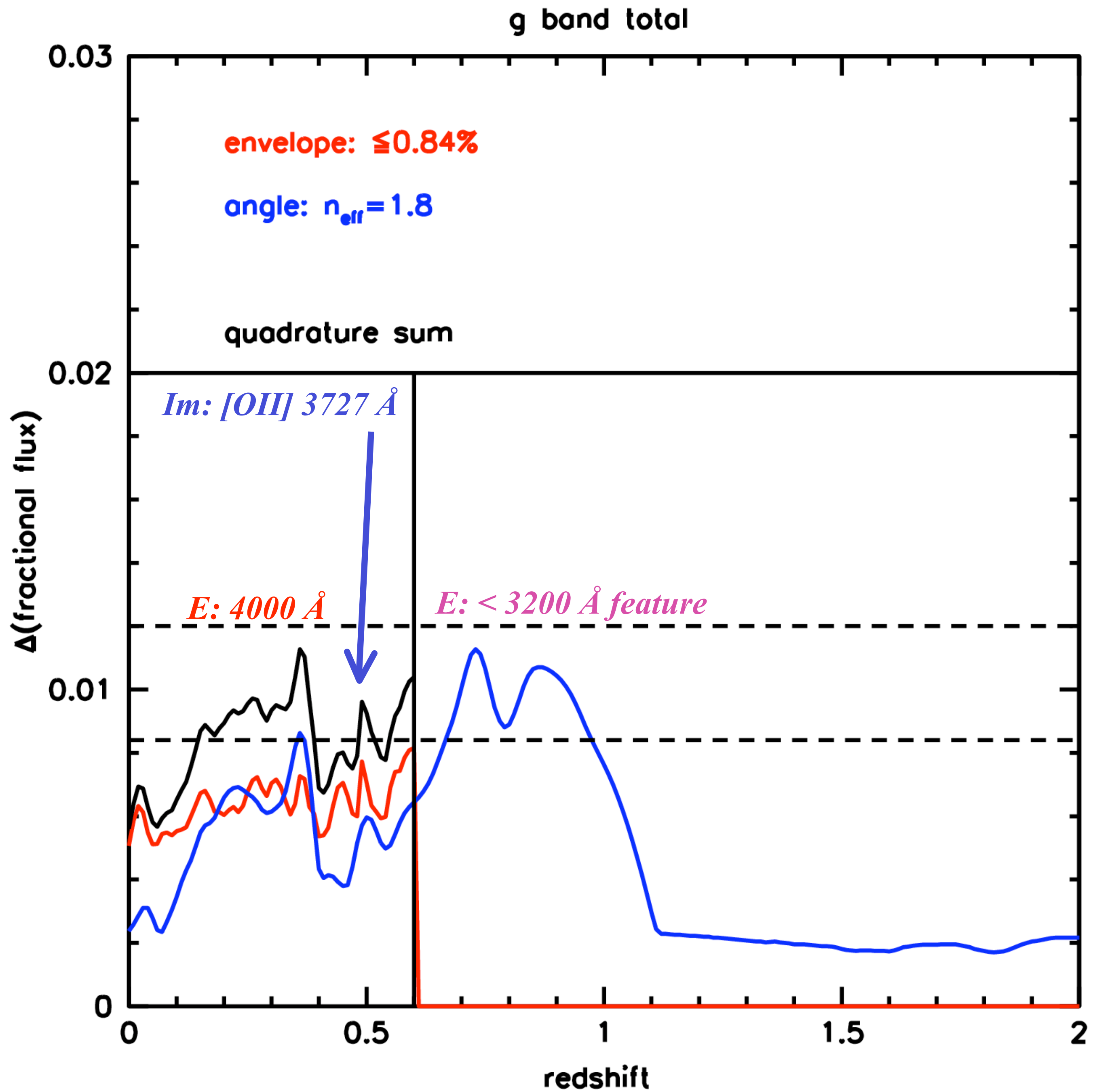
- **Calculate angle of incidence effect for the *average* of trial vendor filter curves**

- **Adopt effective index of refraction estimates from Barr for PanSTARRS filters**
  - $n_{eff} \sim 1.8$ **for g**
  - $n_{eff} \sim 1.75$ **for r**
  - $n_{eff} \sim 1.73$ **for i**
  - $n_{eff} \sim 1.72$ **for z, Z, Y**

- **For incidence angle contribution, take 1/2 of the absolute difference between edge and center fluxes, divided by average of edge and center fluxes**

- **Add in quadrature maximum fractional flux difference for filters within acceptable envelope**


Mauna Kea sky (f_λ)
dark 50%tile conditions
CCD relative QE
(173K, 900 nm = 1)
1.2
1
0.8
0.6
0.4
0.2
0
400
600
800
1000
wavelength (nm)
g
r
i
z
Y


g band total
envelope: ≦0.84%
angle: n_{eff}=1.8
quadrature sum
Im: [OII] 3727 Å
E: 4000 Å
E: < 3200 Å feature
0.03
0.02
0.01
0
0.5
1
1.5
2
Δ(fractional flux)
redshift

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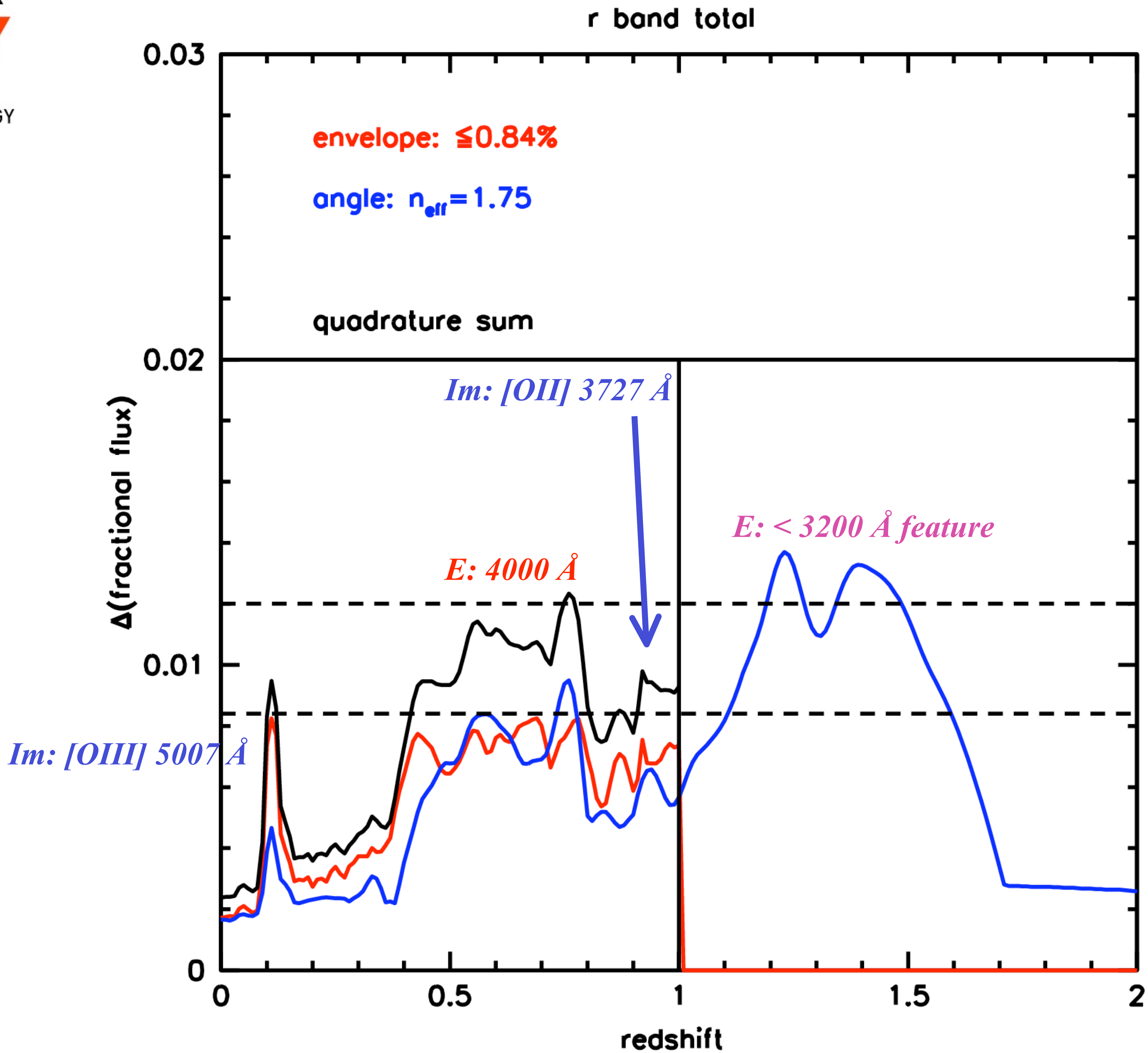
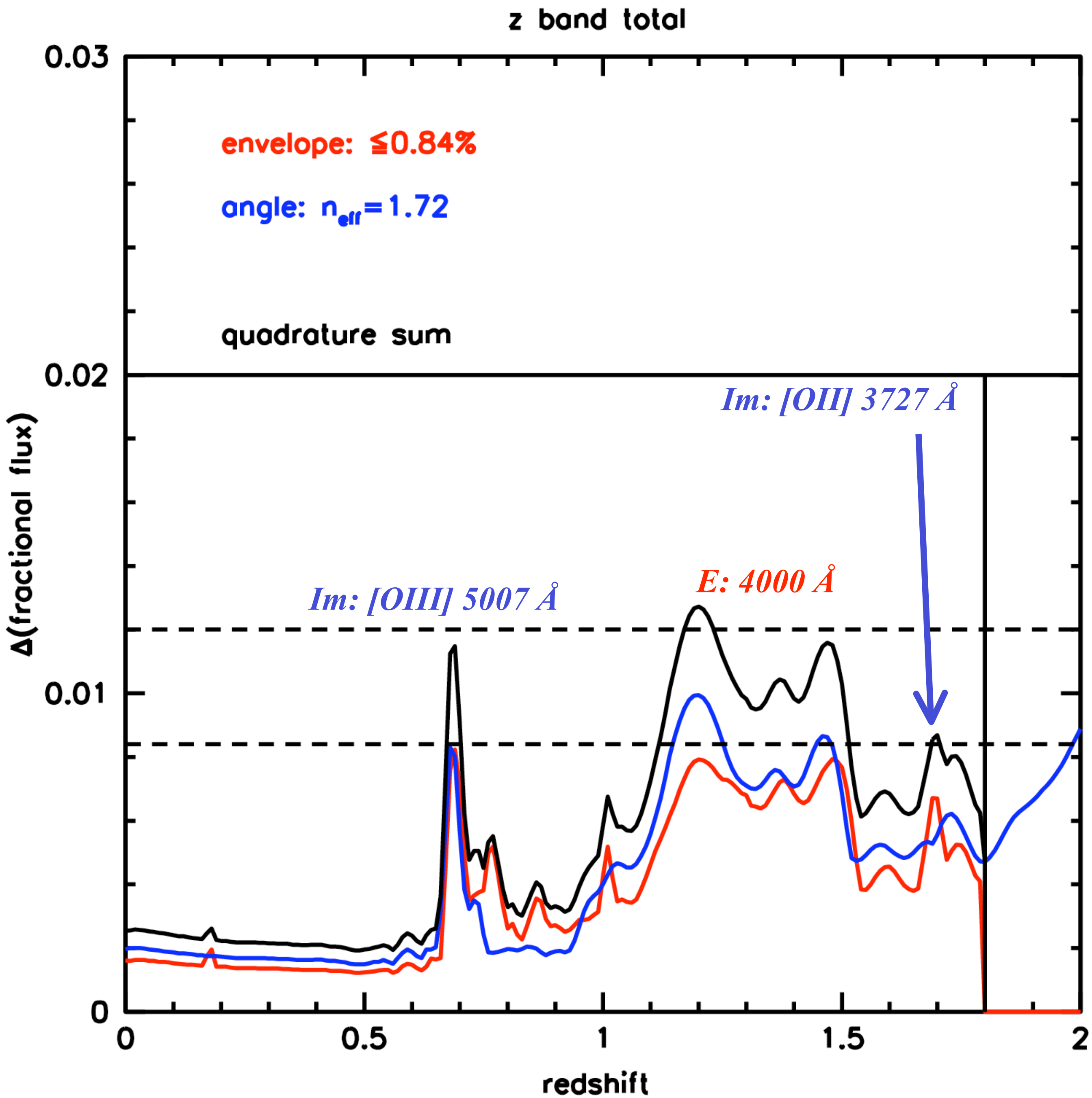
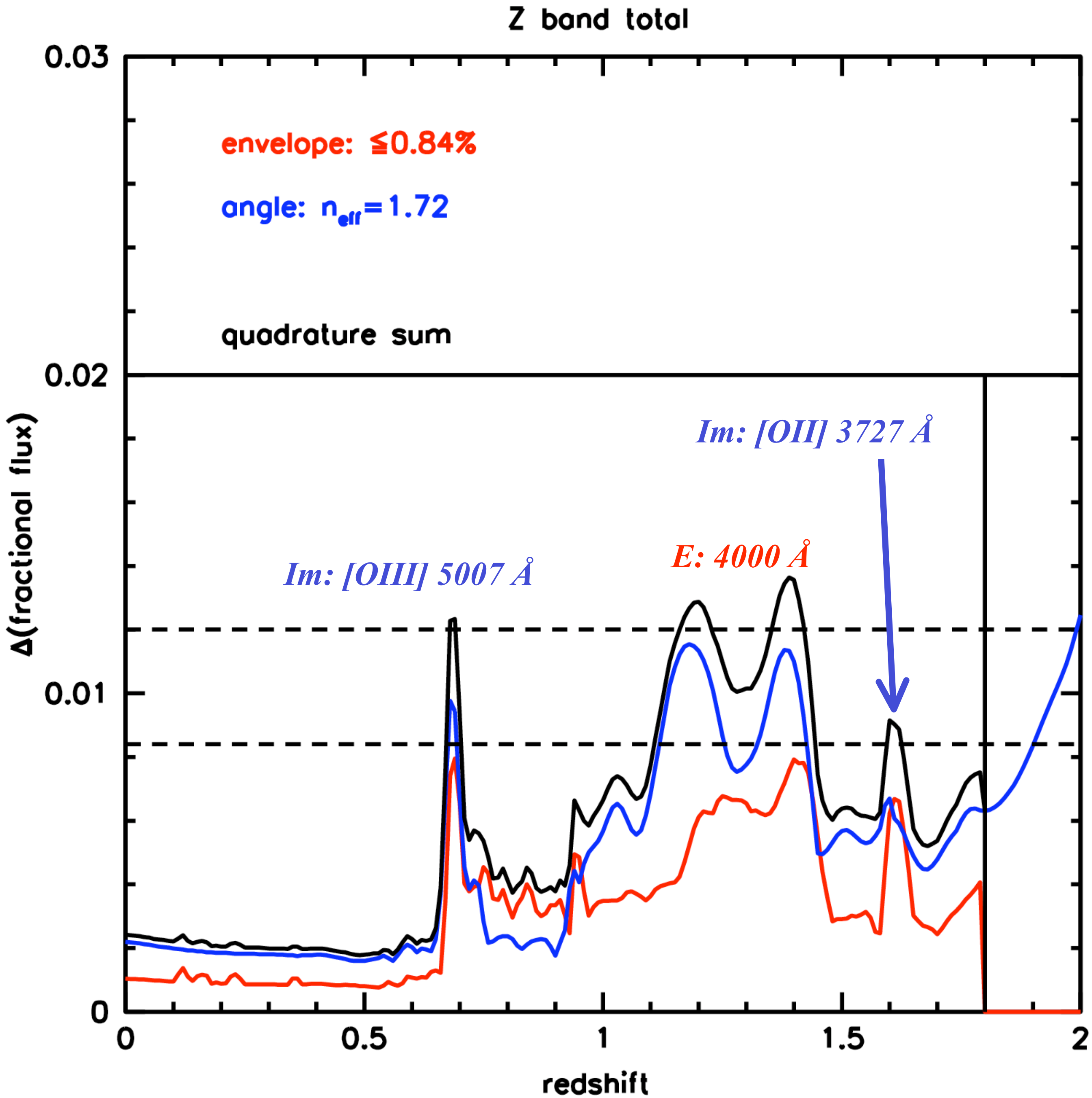
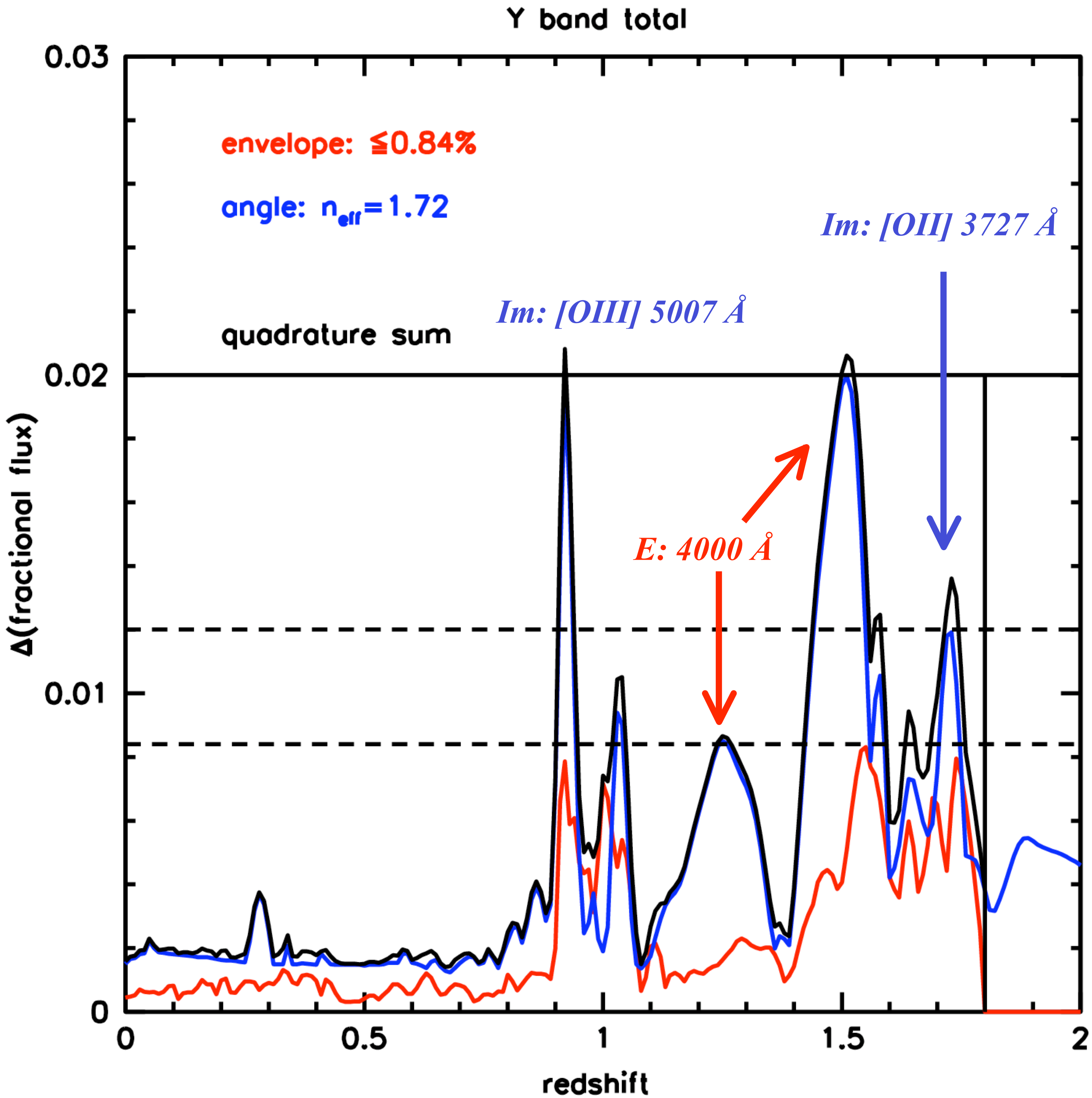



z band total
envelope: ≦0.84%
angle: n_{eff}=1.72
quadrature sum
Im: [OII] 3727 Å
E: 4000 Å
Im: [OIII] 5007 Å
Δ(fractional flux)
redshift
0.03
0.02
0.01
0
0.5
1
1.5
2

DARK ENERGY SURVEY



DARK ENERGY
SURVEY



DARK ENERGY SURVEY

z/Z, Y Filter Issues

- **Need to assess impact of including/excluding variable atmospheric absorption feature at 9300-9600 Å to finalize z/Z bandpass**
  - **Excluding it improves photometric calibration**
  - **Including it improves S/N, e.g., for redshift = 1 elliptical galaxy**
    - **Z (8500-9700 Å) gives 30% better S/N cf. Z (8500-9200 Å)**
    - **z (8500-10000 Å) gives 50% better S/N cf. Z(8500-9200 Å)**
  - **Excluding it improves photometric calibration**
    - **Both LSST and PanSTARRS are using such a Z filter**
    - **Need data on absorption variability to quantify impact on calibration errors**

- **Y filter bandpass**
  - **Consistent with VISTA, LSST, and PanSTARRS choices of blue cutoff**
  - **Need to check DES CCD QE turn-off variability to finalize red cutoff**
  - **Need to define Y-band science requirements to confirm if larger calibration uncertainties (> 2 %) are acceptable**